District Heating Potential and a Danish Heat Atlas Based on Metered Heat Demand Data

Grundahl, Lars

DOI (link to publication from Publisher):
10.5278/vbn.phd.tech.00019

Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

DISTRICT HEATING POTENTIAL AND A DANISH HEAT ATLAS BASED ON METERED HEAT DEMAND DATA

BY
LARS GRUNDAHL

DISSERTATION SUBMITTED 2017

AALBORG UNIVERSITY
DENMARK

DISTRICT HEATING POTENTIAL AND A DANISH HEAT ATLAS BASED ON METERED HEAT DEMAND DATA

by

Lars Grundahl

AALBORG UNIVERSITY
DENMARK

Dissertation submitted 2017

Dissertation submitted: November 2017

PhD supervisor: Prof. Bernd Möller
Aalborg University

Assistant PhD supervisors: Prof. Henrik Lund
Aalborg University

Assistant Prof. Steffen Nielsen
Aalborg University

PhD committee: Associate Professor Carsten Bojesen (chairman)
Aalborg University

Professor Leif Gustavsson
Linnaeus University

Professor Irene Peters
HafenCity University Hamburg

PhD Series: Technical Faculty of IT and Design, Aalborg University

Department: Department of Planning

ISSN (online): 2446-1628
ISBN (online): 978-87-7210-097-5

Published by:
Aalborg University Press
Skjernvej 4A, 2nd floor
DK – 9220 Aalborg Ø
Phone: +45 99407140
aauf@forlag.aau.dk
forlag.aau.dk

Printed in Denmark by Rosendahls, 2017

ENGLISH SUMMARY

District heating is seen as one of the supporting technologies for the transition towards a 100% renewable future in the energy sector. To assess the potential of district heating compared to other heating technologies, mapping of the heat demands is an essential tool.

Heat demand mapping has been used for heat planning in Denmark in many years. Until recently, the mapping was based on statistical knowledge of heat demand in buildings based on the types and ages of the buildings. New developments in data collection have allowed for this data to be supplemented with metered heat demand data collected over a duration of years for more than one million buildings each year.

The thesis investigates the expansion potential of district heating in Denmark under a number of different conditions. Firstly, the economic expansion potential is compared for consumer-economic and socio-economic calculations. The study finds that only approximately half of the potential for each of the economic approaches occur in the same areas. Secondly, the potential is investigated under current conditions and compared to future scenarios with 50% heat savings in space heating and implementation of low-temperature district heating. It is found that low-temperature district heating alone is not enough to mitigate the negative economic impact on district heating arising from substantial heat savings. The implementation of low-temperature district heating has to go hand-in-hand with other measures to improve the economic feasibility of district heating in a future with lower heat demands in buildings.

A new version of the Danish Heat Atlas is developed using the metered heat demand data to estimate the average heat consumption in the different Danish building types. This ensures that heat demand estimates are made individually for all building categories in the Danish Building and Dwelling register. Further, with the new data, it is possible to investigate the accuracy of the heat atlas. This is used to improve the knowledge on how well the heat atlas estimates the actual heat demand depending on the number of buildings included in a sample and across the different building categories.

Finally, an outlook to the heat planning and implementation of district heating outside Denmark puts the focus on the future developments in heat mapping. It further highlights the potential use case for the Danish Heat Atlas as a training tool for heat mapping outside Denmark.

DANSK RESUME

Fjernvarme anses som værende en nøgleteknologi i omstillingen til en 100% vedvarende fremtid for energisektoren. For at kunne bedømme potentialet for fjernvarme sammenlignet med andre varmeteknologier er kortlægning af varmebehov et uundværligt værktøj.

Varmekortlægning er blevet anvendt i forbindelse med varmeplanlægning i Danmark i mange år. Indtil fornyligt var kortlægningen baseret på statistisk viden om varmebehovet i bygninger baseret på bygningstyper og alder på bygningerne. Nye udviklinger inden for dataindsamling tillader at denne viden kan suppleres med værdier for målt varmeforbrug indsamlet over en årrække for mere end en million bygninger hvert år.

Denne afhandling udforsker potentialet for udvidelse af fjernvarmenettet i Danmark under en række forskellige betingelser. Først bliver det økonomiske udvidelsespotentiale sammenlignet for henholdsvis privatøkonomiske og samfundsøkonomiske betingelser. Beregningerne viser, at kun cirka halvdelen af potentialet for hver af de økonomiske beregninger forefindes i det samme områder. Efterfølgende bliver udvidelsespotentialet undersøgt under nuværende betingelser og sammenlignet med fremtidige scenarier med 50% varmebespareler i rumopvarmningen og implementering af lavtemperaturfjernvarme. Det påvises, at lavtemperaturfjernvarme alene ikke er nok til at afbøde de negative økonomiske konsekvenser fra det markant lavere varmebehov. Implementeringen af lavtemperaturfjernvarme skal gå hånd i hånd med andre foranstaltninger for at forbedre den økonomiske mulighed for fjernvarme i en fremtid med lavere varmebehov i bygningerne.

En ny version af det danske varmeatlas er blevet udviklet baseret på målt varmeforbrug, der benyttes til at estimere det gennemsnitlige varmebehov i forskellige danske bygningstyper. Dette sikrer, at varmebehovet estimeres individuel for hver enkelt bygningstype i det danske bygnings- og boligregister. Ved hjælp af det nye data er det også muligt at undersøge nøjagtigheden af varmeatlasset. Det sikrer et kendskab til hvor nøjagtigt varmeatlasset estimere sammenlignet med det faktiske varmeforbrug i henhold til antal af udvalgte bygninger og på tværs af bygningskategorier.

Som opsamling undersøges forventede fremtidige udviklinger inden for varmeplanlægning og implementeringen af fjernvarme i og uden for Danmark. Samtidig fremhæves muligheden for at anvende det danske varmeatlas som træningsværktøj til anvendelse ved varmekortlægning uden for Danmark.

ACKNOWLEDGEMENTS

The work this Ph.D. thesis is based upon was carried out in the period September 2014 to September 2017. The thesis is a result of research activities of the Strategic Research Center for 4th Generation District Heating (4DH), which has received funding from the Innovation Fund Denmark.

Many people have contributed to the scientific content of this work. I would like to thank my main supervisor Bernd Möller for support and fruitful discussions together with feedback on my work during the years. Also, I would like to thank my two co-supervisors, Steffen Nielsen and Henrik Lund, for their support and inputs to my work.

My colleagues in the Research Group of Sustainable Energy Planning have been a great support in the efforts involved in my Ph.D. Both on a professional level where all have been willing to discuss my research with me, and also in creating a pleasant working environment with many talks and events.

I have gained a lot of knowledge from the collaboration with the co-authors of the papers on which this thesis is based. I have learned much from their cooperation, and their collaboration has helped in the development of the content presented in this thesis. Further, I had the opportunity to have a research stay at VITO in Mol, in which I gained a more in-depth knowledge in heat mapping in an international perspective. Especially, I would like to thank Erwin Cornelis who made the collaboration possible and was of great help during my stay.

Finally, I would like to thank my family, and especially my wife Isa, for great support and willingness to talk about district heating and mapping during many times, and my son Oliver for always bringing a smile to my face when I arrive home from work.

LIST OF PUBLICATIONS

The following publications have been produced during the thesis period. The thesis is mainly based upon the papers [1–4], but with [5–9] used to set the context of the work further.

In the bibliography, these publications are included as the first nine entries, and the same numbering is used throughout the thesis when refereeing to the publications. Furthermore, Paper 1-4 is also used when referring to the first four publications, for example, Paper 1 refers to [1].

Primary

[1] Grundahl L, Nielsen S, Lund H, Möller B. Comparison of district heating expansion potential based on consumer-economy or socio-economy. Energy 2016. doi:10.1016/j.energy.2016.05.094.

[2] Nielsen S, Grundahl L. District Heating Expansion Potential with Low-temperature and End-Use Heat Savings, Final draft, submitted for publication n.d.

[3] Grundahl L, Nielsen S. Accuracy in numbers, heat atlas accuracy compared to real-world measurements, in preparation n.d.

[4] Grundahl L, Renders N, Möller B, Cornelis E. Comparing two heat maps developed using different methodologies and data types for the Province of Limburg in the Flemish region of Belgium, Submitted for Journal of Sustainable Energy Planning and Management (Status: under review) n.d.

Secondary

[5] Möller B, Wiechers E, Persson U, Grundahl L, Connolly D. Heat Roadmap Europe - Identifying Local Heat Demand and Supply Areas with a European Thermal Atlas, Final draft, ready for submission n.d

[6] Nielsen S, Grundahl L. Fjernvarmeanalyse i Region Nordjylland,

contribution to report. 2015.

[7] Nielsen S, Grundahl L, Eriksen RB, Jessen K. F & U Energiforbrug i Bygninger. 2017.

[8] Grundahl L, Nielsen S. EnergyMaps 2016. www.energymaps.eu.

[9] Nielsen S, Grundahl L. The Danish Heat Atlas 2016 - Documentation, Draft version 2. 2016.

TABLE OF CONTENTS

CHAPTER 1. INTRODUCTION

The topic of district heating and its role in the future renewable energy system is being introduced. It is explained how district heating can form part of the way towards the overall goal of reaching a 100% renewable energy system. It is further explained how the Danish Heat Atlas as a tool can support the planning of district heating. Although the overall focus is related to the heating sector, it is an integrated part of the pathway towards a 100% renewable energy system where all the main energy sectors are integrated. District heating can be a key technology to enable this form of integration and heat atlases are one of the essential tools used to ensure a high awareness of the potentials of district heating in the heating sector and the initial estimations of the district heating potential.

1.1. THE PATHWAY TO A 100% RENEWABLE ENERGY SYSTEM

Across the world, there is a high focus on reducing the emissions of greenhouse gasses and subsequently limiting the impact of climate change. The aim of reducing the emissions of greenhouse gasses goes hand-in-hand with re-direction of national energy policies as a substantial part of the greenhouse gas emissions are occurring in the four energy sectors; heating, electricity, gas, and transportation. Denmark, like many other countries, has a number of goals and ambitions to reduce the climate impact and reduce the use of fossil fuels. The driver behind many of the implemented policies is the fulfillment of international obligations in the European Union and the United Nations [10].

According to the government platform of the Danish government, the long-term goal for the energy sectors in Denmark is to completely phase out all fossil fuels by 2050 [11]. As intermediate goals, Denmark is following targets set in the European Union. The specific target for Denmark in 2020 is 30 percent renewable energy in the total energy consumption [10]. The Danish government further aims for 50 percent renewable energy in 2030 [11].

Several studies addressed the topic of 100% renewable energy systems. Two studies for the case of Denmark are the IDA Climate Plan 2050 [12] and the IDA Energy Vision 2050 [13] supported by the paper [14]. Both plans lay out pathways for a transformation of the energy system towards 100% renewable energy. Several major steps are involved in this transformation, including large efforts to reduce the energy consumption, and changes in the production methods for energy to include renewable sources only. Similar studies are made for other countries for example [15], which investigates the transition towards a 100% renewable energy system in the case of Ireland and [16] looking at a renewable energy scenario for the Jiangsu province in China. Many of these analyses build upon the concept of Smart Energy Systems, which is a 100% renewable energy system utilizing the synergies between the different energy sectors to maximize the efficiency and reduce the costs [17–21].

The reduction of energy demand is needed across all energy sectors. For the heating sector, reducing the energy demand requires changes to the building stock. In Denmark, the building regulations have been consistently increasing the requirements to the energy performance of new buildings. However, it is in the existing building stock that the largest energy consumption occurs. Energy conservation in the existing building stock requires improvements to the energy performance of the buildings and should be done as an additional marginal investment when renovations are required anyway [22]. Through the utilization of a regularly updated heat atlas, the energy consumption status of the building stock can be monitored and used in energy system modeling. Further, forecasting of expected changes to the energy consumption in the building stock is possible.

A major challenge in the transformation towards a 100% renewable energy system is the step away from a fuel based system. In the traditional energy system fuel is burned to produce energy; this is the case in the traditional electricity, heating and transportation sectors. The fuel can be stored and enables production when demand is present. However, with many of the renewable energy sources, production is bound to the fluctuating input energy, be that wind, solar, water or others. Biomass is still a fuel based energy source where the fuel can be stored. However, biomass is a limited resource and therefore cannot provide the same degree of flexibility in terms of quantity as the vast amounts of fossil fuels used in the current system. [23]

The flexibility in the system enabling it to meet the demand is therefore no longer in the fuels. Instead, other means of flexibility has to be enabled in the system. One such way is to implement a higher degree of sector integration, where energy from one sector can be utilized in one or more of the other sectors. This sector integration can both work two-ways so that the energy afterward can be transferred back, or one-way where the energy is transformed and used in another sector. [24]

Together with the sector integration storage of energy is still a necessity for the balance of the energy system. This again can be done across the sectors to ensure a balance between supply and demand and an economically feasible system.

1.2. THE IMPLEMENTATION OF RENEWABLE ENERGY IN THE ENERGY SYSTEM

High levels of renewable energy in the energy system are likely to increase the complexity of the system design and increase the need for balancing services in the system. The implementation of energy savings further enables the transition to a renewable energy system. Higher levels of energy storage can ensure that energy can be produced when the intermittent resources are available and stored for later consumption. However, storage options are not equally financially and technically feasible across sectors.

1.2.1. INTEGRATION OF ENERGY SECTORS

Co-production of energy happens already today, for example in combined heat and power plants. Here, the heat produced as part of the process of electricity production is utilized for heating purposes [25,26]. This integration is often permitted by the use of district heating. In the future, other types of coproduction units are expected to appear. This can, for example, be units for electro fuels, where CO_2 recycling paired with water electrolysis allows for fuel production through the process of CO_2 hydrogenation, which also has a surplus of heat production usable in for example district heating networks [27]. At the same time, they convert electricity to fuels for the transportation sector. To a large extent co-production, today is connected with the utilization of district heating to absorb the large amounts of heat produced.

Another type of integration happens with units converting one form of energy to another. Examples of these are heat pumps and electric boilers, which use electricity as an input for heat production. This transforms surplus electricity into useful energy for the heating sector [28–30]. Heat pumps have the benefit of a higher coefficient of performance resulting in a higher heat output using the same amount of electricity. On the other hand, they have a higher investment cost compared to electric boilers and a mix of both is expected to appear in the future optimizing the ratio between investment and operation costs. Heat pumps are likely to be best used in applications as base load or with many operation hours, whereas electric boilers can be used as peak load units or conversion units to absorb peaks in the electricity production. Heat pumps and electric boilers exist both in small-scale applications for individual households and in large-scale applications suitable for implementation in district heating networks.

Apart from sector integration, flexible demands are also expected to form part of the future energy system enabling consumption to be shifted and better match the production. Flexible demands can be applied in the different sectors using for example pricing schemes to encourage the consumers to shift their consumption to times with more production. Examples of pricing schemes are Real-time pricing, Time of use tariff or critical peak pricing [31]. This, together with sectorial integration can enable higher amounts of fluctuating energy sources in the energy system.

Large-scale sectorial integration between the heating sector and the gas and electricity sectors can be realized with a district heating system. District heating can absorb large amounts of surplus heat from excess electricity conversion, industrial processes, fuel production, etc., and store the heat for later consumption at lower costs than electricity storage or as heat storage integrated into individual households [32].

1.2.2. ENERGY STORAGE IN AN INTEGRATED SYSTEM

The integration of energy systems includes the transfer of energy from one sector in surplus to another for either consumption or storage. All energy sectors need to be balanced over time, meaning that production needs to meet the demand over time. However, the timescale for the balance is very different between the sectors [32].

In the electricity sector, the balance needs to be instantaneous. Otherwise, the frequency in the grid will fluctuate. Therefore, electricity units are needed as reserve capacity to ensure balance in the system. When adding renewable energy sources such as wind or solar energy to the system, the balancing becomes more complicated since the production becomes more unpredictable and to some degree less controllable. In times of surplus production, the balance can be maintained in three different ways. First, the production can be lowered, which traditionally meant burning less fuel. With renewables, this instead means stopping production by for example shutting down wind turbines. This does not save fuel for later use but instead just leaves a lost opportunity for energy production. The second method is by storing the energy in for example batteries or in pumped hydro. Currently pumped hydro accounts for over 90 percent of the global storage capacity [33]. Electricity storage, however, is often a costly method and might not be feasible on a large scale except when needed to ensure balance in the electricity system or the transportation sector. Thirdly, the electricity can be converted into other forms of energy such as heat or gas and either used directly or stored in one of these forms.

In the thermal sector, the balance in the system can vary between hours, days and even months depending on the system at hand. If the thermal system is on a per-household basis, it is possible to produce and store energy for several hours in a hot water tank for hot water consumption or space heating. If the system is on a larger scale, for example in the form of a district heating system, storage can be possible for several days and in some cases even months if a seasonal storage is in operation [34]. The amount of flexibility in the thermal storage depends on the size, and larger centralized storages allow for a higher flexibility and more prolonged storage periods. [25]

Balance in the gas sector is achieved by storing gas in the pipes and storage facilities. It is possible to store the gas for longer time periods in large caverns, and in Denmark, the existing gas storages caverns have a capacity of approximately two months consumption [35]. The gas storage facilities are used to match supply and demand by handing the imbalance between seasonal variations in gas consumption and a more regular flow from the production sites [36]. The gas sector can absorb large amounts of energy from the other sectors by utilizing the already existing storage capacity.

The transportation sector is a major challenge in the pathway to 100% renewable energy. Several options for renewable energy in the transportation sector already exist with biofuels and electricity [37]. Many studies suggest a mix of energy sources for the transportation sector with lighter vehicles and for example trains running on electricity and more heavy transportation like ships running on biofuels. However, the reality is likely to be more diverse with some ships already today running on electricity, for example, ferries on shorter routes, and some cars running on biofuels. Storage in the transportation sector can be as either gas or liquid for biofuels and electro fuels or in batteries for pure electric transportation. Both forms of storage can store energy for days or more.

Other than the time perspective in the balancing of the different sectors, the cost of storage also varies largely [32]. It can, therefore, be feasible to convert the energy into either heat or gas for a cheaper and more long-term storage option. For the heating sector, this requires a system allowing large-scale storage. Implementing district heating allows large-scale heat storage with the added benefit of a longer time-scale for balancing the demand and production.

1.2.3. 4TH GENERATION DISTRICT HEATING

Heating accounts for a significant share of the total energy consumption. For the European Union, it is estimated that buildings alone use 40 percent of the final energy. The predominant part of this is for space heating and hot water [38]. The European Commission has launched an EU heating and cooling strategy, which amongst other things aims to better integrate the electricity system with district heating and cooling systems. Further, the strategy aims to reduce the energy waste in the industry by linking the industry with district heating systems. [39]

District heating is a well-known technology dating back more than 100 years. It works with a central production of heat, which is then transferred to the consumers through a pipe network. Many of the first applications were steam based with temperatures above 100°C. Over time, it has become more common with water-based systems with lower temperatures and higher efficiencies. Today, most systems operate as the so-called third generation system using insolated pipes and forward temperatures of 70-80°C. The relatively high temperatures, however, result in high heat losses. Further, it makes it challenging to integrate low-temperature excess heat sources or production units like heat pumps, which operates more efficiently at lower temperatures. Therefore, a lot of research today is focused on the fourth generation of district heating.

In fourth generation district heating, the temperatures are expected to decrease further with forward temperatures reaching 50-60°C. This will enable more sources of energy to be implemented in the system as well as increase the efficiency of for example heat pumps producing energy for the district heating system. [40]

The overall nature of district heating is not expected to change. The production is done on central units, although with a bigger variation in types of unit and potential more smaller units rather than a few large ones. The heat is then transferred to the customer through a pipe network. Included in the system will be storage units, which can be used for different purposes. They can be operated to balance the system on a short-term scale ensuring that enough heat is available for the consumers without changing the production all the time. They can be used for peak shaving enabling a stable production to meet a fluctuating demand, or they can be used to store production on a large time-scale to enable production units with production patterns very different from the consumption pattern. The latter case is already seen in many networks in Denmark today where solar heating is used in combination with a seasonal storage. [32,41]

District heating in the third generation already possesses many of the characteristics needed to be part of a future 100% renewable energy system. It can absorb large amounts of energy from other sectors and can store much of it for later use. With the fourth generation of district heating, the system is optimized even further as it can integrate more heat sources at lower temperatures, adding to the flexibility of the system. At the same time, the lower temperature in the district heating grids will enable a higher efficiency of heat pumps utilizing the electrical energy better in the system. Even further, the fourth generation of district heating will better match the lower heating needs of future buildings enabling district heating to stay relevant as a heating technology. [40]

The transformation towards a 100% renewable energy system requires many changes within the different sectors. This thesis will focus on the heating sector and the role of district heating in the transition towards a 100% renewable energy system.

CHAPTER 2. HEAT PLANNING

This chapter describes heat planning in Denmark. It further describes how spatial heat mapping is used as an important input to the process of heat planning. Lastly, it is used to define some of the terms and concepts used throughout the thesis.

2.1. HEAT PLANNING IN A DANISH CONTEXT

Historically, heat planning in Denmark started as a response to the oil crises in the 1970s with the implementation of the first heat supply act in 1979 [42]. This initiated a process in which heat planning became part of the regulatory function of the Danish municipalities.

Today, heat planning in Denmark follows the same overall structure as general planning in Denmark. This means that it to a large degree is decentralized where the municipalities are responsible for the local planning [43]. The Danish regions are responsible for regional development plans and the overall framework for decision making is established in the national planning defined by the government and the Danish Parliament. [44]

The national framework is often influenced by international obligations through the membership of the European Union and other international collaborations such as climate agreements. The parliament is also responsible for the Heat Supply Act[1] and thereby sets the overall planning framework for heat planning and district heating. The Heat Supply Act, for example, incorporates clauses from the European Parliament regarding energy efficiency [45]. Most often the responsibility of writing the legislation regarding heat planning falls with the Danish Ministry of Energy, Utilities and Climate[2] [46].

The next level in Danish planning is the regional planning, which occurs in the five Danish regions. Although no obligations exist for the Danish regions in the heat supply act, it is evident from the projects presented in this thesis that they still partake an active role in heat planning. The regions initiated investigations of the potential of district heating expansions in [6,47] enabling a perspective which crosses the municipality borders. However, the regions are formally only responsible for regional development plans, which envision how the regions foresee the future and have a strong focus on business development. They do not have regulatory power in the planning process and are not obligated to make visions for heat planning.

---

[1] Varmeforsyningsloven

[2] Energi-, Forsynings- og Klimaministeriet

The larger part of heat planning happens in the Danish municipalities following the heat supply act [45]. The municipalities are obliged to take part in the planning of the local heat supply and often do this in close collaboration with the local utility companies. The local planning is happening in the municipalities, and they are the ones in charge of the local heat supply plans. Further, in some cases, the municipalities also own the local district heating utilities. This means that in these cases they both have the responsibility for the heat planning and the ownership of the heating network. Alternatively, the district heating can be privately owned by either a company or the consumers. In such cases, the municipality is less involved in the operation of the district heating system.

It is the responsibility of the municipalities to investigate whether it is possible to establish communal heat supply within the municipality borders. Often, the investigation is done for areas where district heating could potentially be feasible, for example, new urban areas in connection with existing towns and close to existing district heating networks. The investigation is often carried out in collaboration with the utility company operating the district heating network. Furthermore, they can order the existing utility companies to implement an approved district heating project and can enforce consumers to connect or stay connected to communal heat supply [48].

A number of actors also exist to monitor and support the progress in the planning process. Several of these also influence the heat planning. Most notable are the Danish Energy Agency[3] and the Danish Energy Regulatory Authority[4]. These two actors help to shape the legal framework for the district heating companies in Denmark and are responsible for the correct implementation of the heating systems in Denmark [49,50].

2.1.1. THE HISTORICAL BACKGROUND FOR HEAT PLANNING IN DENMARK

The historical background for heat planning in Denmark takes a starting point in the oil crisis, which hit the world in 1973 and 1979. Previously, the Danish energy system was predominantly supplied by imported oil across all energy sectors. The Danish economy, therefore, took a hard hit from the oil crises and efforts were initiated to reduce the dependence on oil.

One of the efforts was the initiation of energy planning on a national level. The first official energy plan from 1976 was focused on three main issues:

1. Conversion from oil to coal and nuclear power for the electricity sector.

[3] Energistyrelsen

[4] Energitilsynet

2. Establishing a nation-wide natural gas network.
3. Conduct heat planning in all counties and municipalities in preparation for heat savings.

Except for the implementation of nuclear power, all of the above were accomplished in the following years [51]. As a response to the first official energy plan, which only contained one scenario including nuclear power, the first alternative energy plan was also presented in 1976. This first alternative energy plan aimed at a higher implementation of renewable energy sources and a system without nuclear power [52]. A tradition for alternative energy plans with a high focus on renewable energy sources was thereby initiated which continues today with for example [12,13].

With the heat supply act implemented in 1979, the municipalities together with the counties and the Ministry of Energy were made responsible for investigating the potential for communal heating. This included both district heating and natural gas networks. District heating was already present in many towns across Denmark, but the implementation had been based on local needs rather than a nation-wide planning process. The purpose of the law was to ensure the socio-economically most feasible heating option and reduce the dependency on oil. A nation-wide heat planning was initiated, and the municipalities were made responsible for mapping the local heat demands and excess heat availability. Municipal heat plans had to comply with the overall targets in heat plans developed on a national level. These furthermore, had to be approved by the Ministry of Energy. [53]

The national heat planning took place in the years 1981-1982 and included geographical delimitation of heat supply zones for district heating and natural gas to ensure that gas pipelines and district heating networks are not developed in the same areas [54]. The 1986 energy agreement focused on energy savings and future expansion of the electric generation capacity with decentralized combined heat and power plants, sparking the development of domestic natural gas as a fuel source for district heating [55]. In 1990, a new energy agreement again focused on the implementation of combined heat and power plants, this time by replacing heat only boilers [56]. This implementation ensured a rapid growth in both district heating and natural gas networks in Denmark. Further, it ensured a rapid change in fuels used for district heating, which before the oil crises had predominantly been oil. Within a period of approximately 15 years, a mix of alternatives replaced the majority of the oil consumption as seen in Figure 1.

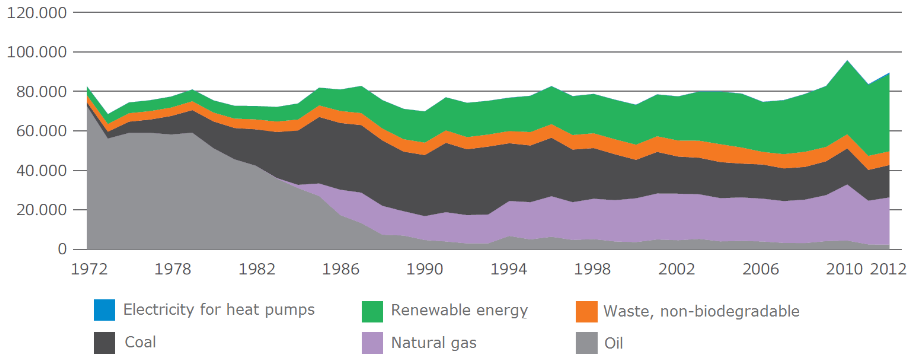

Figure 1: Fuel for district heating production in PJ based on statistics from the Danish Energy Agency. Adjusted from [57].

The 1990 energy agreement resulted in a transition from production on heat only boilers to combined heat and power plants fueled by natural gas, see Figure 2. In this way, the electricity production was increased, and heat and electricity production was made more fuel-efficient. Figure 2 also shows that the leading trend in recent years is going towards more production on heat only boilers and less on decentralized combined heat and power plants. This is linked to the increased amount of renewable energy seen in Figure 1 which largely is biomass used in heat only boilers. The decrease in production on combined heat and power plants is largely tied to low prices on the electricity market and high prices on the natural gas market in the later years.

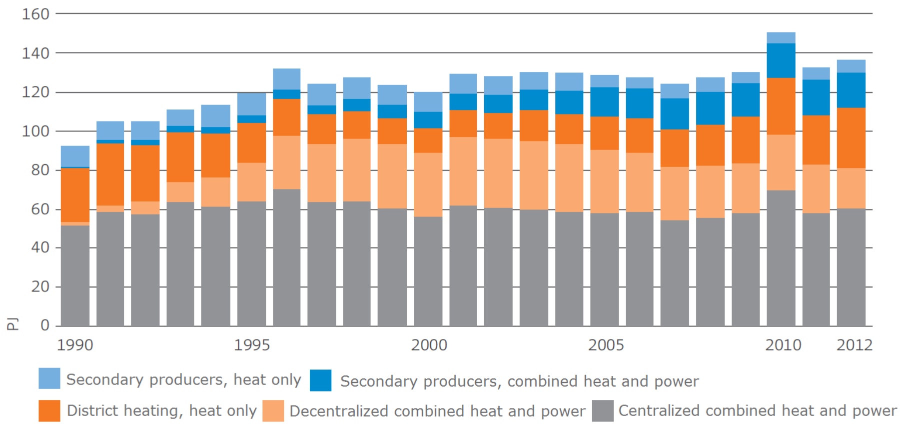

Figure 2: District heating production structure based on statistics from the Danish Energy Agency. Adjusted from [57].

In the 1990's the full responsibility of heat planning was placed in the municipalities. Unfortunately, this meant that district heating and heat planning in many areas were less on the agenda in this period, partly because of a lack of modeled heat demands available for the municipalities, further explained in Section 2.2. Furthermore, it resulted in less focus on heating solutions across municipality borders. As a result, the expansion of the district heating networks slowed down in this period. [42] Figure 3 shows the development in consumption of district heating and natural gas in the period 1966-2016. The Figure confirms that district heating already was present in Denmark before the active heat planning begun. However, the growth increased rapidly in the 1970's and 1980's and continued with a somewhat slower rate in the 1990s and 2000s. For natural gas, it is clear to see that a very rapid implementation started in the 1980s and continued in the 1990s before slowing down and decreasing in the following years.

The developments on the oil markets in the 1970's initiated a process of active heat planning in Denmark. A normative approach was established with a focus on planning district heating and natural gas. This also generated a need for access to data and mapping for heat planning, and data collection was initiated with for example the Danish building and dwelling register, which will be explained further in Section 4.1.

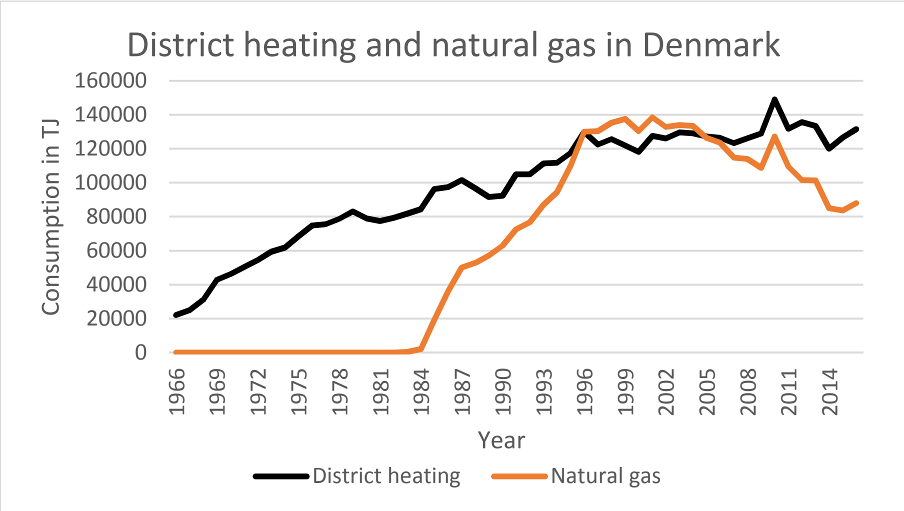

Figure 3: District heating and natural gas consumption in Denmark from 1966 until 2016 [58]. *The natural gas consumption was converted from Nm^3 to TJ based on* [59].

The heat planning in Denmark started as a response to the oil crisis but has over time been implemented as an integrated part of the more long-term planning process in Denmark. Today, the majority of the heat planning happens in the municipalities but as the next section highlights the local planning is often hindered by the lack of access to data on heat demand.

2.2. SPATIAL INFORMATION IN HEAT PLANNING

Mapping of heat demands and supply areas has long been a part of heat planning in Denmark. The mapping of supply areas started in the mid-1970s. It was done by the municipalities and initially on analog maps as energy districts. Later the Danish Energy Agency established a database called Energidata in collaboration with the municipalities and in the process the analog maps were digitalized. The system was built upon energy districts with information on space heating, electricity consumption, and industrial processes. In the late 1990s, the data was made available online, and the database was maintained and updated until 2007. [60,61]

Following the expiration of the updates in 2007 of the Energidata database modeled heat consumption data was no longer available at a central point. This meant that Danish municipalities and other institutions involved in planning no longer had access to a central register of modeled heat consumption data and therefore were limited in their abilities to do heat plans. The process of heat planning, therefore, became more complicated demanding an effort to be put in developing heat demand data or paying others for the service.

A common geographic database for the municipalities called PlansystemDK was established in 2006. PlansystemDK hosts spatial explicit information on all plans regarding land use, zoning, water, nature conservation and more in the municipalities and has it available in an online application. This includes district heating and natural gas supply areas, but, contrary to Energidata, without heat consumption data. The individual plans are administrated and updated by the municipalities [62]. The use of PlansystemDK in this thesis is further explained in Section 4.3.

Heat demand mapping is an important part of heat planning. When generating the energy districts, heat demands were part of the information modeled and in the process, they were put in a spatial context. Spatial heat demand mapping still forms an important part of the planning process for district heating, but consultants and researchers have taken over from national planning authorities, and the municipalities no longer have access to a central register of modeled energy demands. In the heat atlas developed at Aalborg University, the heat demands are estimated on the level of the individual buildings and can be summarized on any spatial entity with a lower resolution. The heat atlas has been used in several studies over time, including Paper 1-3 and [6–9]. Other examples are [63–67] in which the heat atlas is used in a context of heat demand mapping and investigations of district heating potentials.

The heat atlas is a generalized model for heat demands in Danish buildings in heat planning in Denmark. With estimates on heat demand in individual buildings, it is possible to use it as a screening tool for the potential of district heating. The heat atlas is not aimed at predicting the exact heat demand of individual buildings but rather to work based on generalized methods to estimate the average consumption of specific types of buildings. This allows it to be used to calculate the economic potential of district heating versus individual heating options. Furthermore, the approach can be utilized for several areas at a time allowing for an easy screening of areas with a high potential for district heating. Following this, more detailed calculations on the economic consequences of district heating can be carried out in the areas with the highest potential. The heat atlas is thus able to support the local planning and provide the data needed to identify potential areas for district heating.

A challenge for the heat atlas has been the lack of knowledge on the accuracy of the consumer heat demand model used to estimate the heat demand of the individual buildings. Furthermore, there is a potential for improving the usage of the spatial location of the individual buildings when doing economic calculations of for example the district heating grids.

CHAPTER 3. RESEARCH QUESTION

This chapter will present the scope of the thesis, the problem statement, and the structure of the thesis. The heating sector, as stated in Chapter 1, will be an integrated part of the overall energy system and the changes within the heating sector, therefore, have to reflect the expectations from the other sectors.

3.1. SCOPE OF THE THESIS

The thesis tries to grasp the relatively broad topic of heat planning and heat atlases, with a special focus on the Danish case. However, there are many topics within this field, which have to be left outside the scope of the thesis. The focus of the thesis is on the heat consumption in buildings and the mapping of the heat consumption. Furthermore, it focuses on the potential of district heating based on the heat demand of the individual consumers and the district heating networks used to distribute the heating. This corresponds to the upper half of Figure 4. The focus is therefore not on the specific production methods and the direct integration with other sectors in the energy system corresponding to the lower half of Figure 4. Overall, the thesis aims to improve the knowledge and accuracy of a geographical consumer heat demand model and improve the distribution grid model for economic calculations when using the heat atlas as a screening tool

Furthermore, the thesis ends with an outlook to the case of district heating in Europe, looking at the potential use cases for heat atlases and heat demand mapping in a European context.

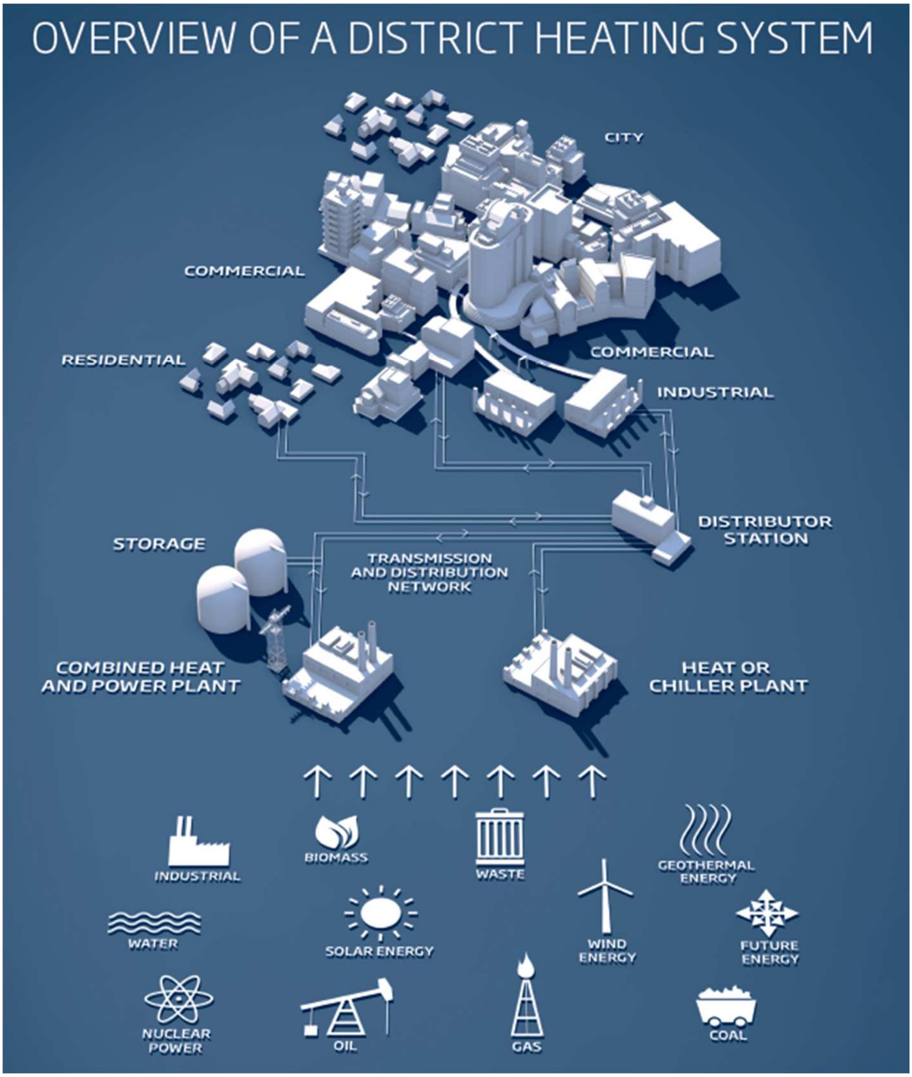

Figure 4: Overview of a district heating system. The thesis aims at improving the knowledge and ability to calculate the economic feasibility of the upper half of the figure; the consumers and their location and heat demand and the location and size of the heating grids. The Figure is from [68].

3.2. PROBLEM STATEMENT

The thesis is built upon a series of objectives to outline the goals of the work done during the duration of the Ph.D. These objectives are outlined below:

- Gain knowledge on the district heating planning process and how the mapping of heat demands can assist in the process.
- Develop an updated edition of the Danish Heat Atlas based on consumer data.
- Refine the method used for economic assessment of district heating potentials.
- Investigate the potential usage of mapping of heat demands outside Denmark and how the Danish experience can be utilized in the process.

These objectives lead to the following problem statement:

> *How is it possible to integrate metered consumption data in the heat demand estimations of the Danish Heat Atlas and to further improve the usability of the heat atlas as a screening tool for economic assessments of district heating potentials?*

3.3. THESIS STRUCTURE

The structure of the thesis and the connection with the publications seen in the List of Publications is described in the following.

Chapter 1 introduces the context in which the thesis has been developed. It describes the focus on the transition towards a 100% renewable future in which district heating can play a crucial role. Further, it explains some of the benefits of district heating and especially 4th generation district heating in a more integrated energy system.

Chapter 2 describes the process for heat planning in Denmark and how spatial information can be utilized in the process. The chapter answers the first of the thesis objectives.

Chapter 3 defines the research question and the scope of the thesis. Furthermore, it describes the structure of the thesis and the connection between the chapters in the thesis and the publications included in the list of publications.

Chapter 4 is describing the data collection for the work done in the thesis. It describes the Danish building and dwelling register, the FIE database and mapping services in Denmark. It also describes the data sources from outside of Denmark used in Paper 4.

Chapter 5 focuses on the spatial and economic analysis of the expansion potential of district heating. The chapter takes a starting point in the work done in Paper 1 as well as in the reports [6,47]. The studies introduced in the chapter is used as a baseline for further improvements of the Danish Heat Atlas.

Chapter 6 describes the work done in developing the latest version of the heat atlas using meter heat consumption data as an input to the model, which is linked to the project described in [7] as well as the development of the online access point to the heat atlas [8]. It further describes the work done to validate the accuracy of the heat atlas and to ensure better results when using it as a screening tool for district heating projects. This part of the chapter is based on the work done in Paper 2 and Paper 3. The work done in this chapter is focused on the objectives of updating the Danish Heat Atlas based on consumer data as well as refining the methods used for economic assessment of district heating potentials.

Chapter 7 intends to put a more international perspective on heat demand mapping and the usefulness of heat atlases. It is partly based on the work done in Paper 4 but also tries to look more broadly on the applicability of heat mapping and how the Danish Heat Atlas can be used in an international context. The Chapter is focusing on the thesis objective of investigating the potential usage of mapping of heat demands outside Denmark. It further looks at which parts of the Danish experience that can be used in the setting of other countries with different data availability.

Chapter 8 recapitulates on the work described in the papers and the thesis and also discusses the outcomes of the work done during the Ph.D.

Chapter 9 concludes on the thesis.

CHAPTER 4. DATA COLLECTION

This chapter focuses on describing the different databases used to collect data for the work with the Danish Heat Atlas. These are the main registers used to collect data about buildings, their heat consumption and geographical information about Denmark and the Danish planning system. Furthermore, it describes the data used for the generation of the heat atlases used in Paper 4.

4.1. THE BUILDING AND DWELLING REGISTER

The building and dwelling register (BBR) was initiated in 1976 with the passing of the act on building and dwelling registration[5] [69]. All municipalities had to establish a register of buildings and dwellings within their borders. The registers were to follow national guidance according to the minister of housing in order to ensure a uniform way of registering and make a foundation for a national register. The register was kept in the municipalities, but the individual owners of the buildings were made responsible for providing the input data. This is similar to the way the register is being operated today. [69,70]

To maintain a uniform way of registering all buildings a circular on establishing the building and dwelling register was provided to the municipalities [71]. Examples of how the circular ensures a uniform registration are sections 22 and 23, in which it is defined how to number the floors in multistory buildings and number the individual apartments on floors with more than one apartment, respectively. This uniform way of registering data implemented in 1977 is fundamental for the use of data from BBR in today's work with for example heat atlases. Another important aspect to highlight is that the circular also ensured that the registration of housing address in the Danish Civil Registration System and the BBR system are aligned.

In 1977, as part of the BBR, the building usage codes were also introduced [72]. The usage codes have the purpose of describing the usage of the building based on the type of activities the building is used for. These codes are maintained in the BBR today and are used in the development of the Danish Heat Atlas, see Table 1. Further, the registration for each individual building includes, amongst other things, year of construction, location, and size, which are all used in the development of the Danish Heat Atlas. The BBR also contains information about the heat installation in the buildings and fuel type used for the current heat production. However, especially for the heat installations the register is sometimes not updated when changes are made in the buildings and this information has to be used with caution.

[5] Lov om bygnings- og boligregistrering

Table 1: Building usage categories [9].

Anv	English
110	Farmhouse at agricultural holding
120	Detached single-family house
130	Terrace-, linked or double house (horizontal separation between units)
140	A building of flats (A house for multiple families including two family housing (Vertical separation between units)
150	Dormitory
160	Residential home (for elderly, for children or for young persons)
190	Other building for residence all year round
210	Commercial production regarding agriculture, forestry, market garden, nursery, raw material extraction, a.o.
220	Commercial production regarding industry, trades a.o. (Factory, workshop, a.o.)
230	Power station, gasworks, waterworks, district heating station, incineration plant, a.o.
290	Other building for production and storage in connection to farming, industry, a.o.
310	Transportation and parking facility (cargo hall, airport building, train station, a.o.
320	Wholesale trade and storage
330	Retailers, a.o.
390	Other building for trade and transport, a.o.
410	Cinema, theater, commercial exhibition, a.o.
420	Library, museum, church, a.o.
430	Education and research (School, gymnasium, research laboratory)
440	Hospital, maternity home, a.o.
490	Other institutions, including barracks, prison, a.o.
510	Holliday cottage
520	Unit for holiday purposes not a Holiday cottage (Holiday camp, youth hostel, a.o.)
530	Unit linked to sport (clubhouse, sports center, swimming bath, a.o.)
540	Allotment hut
590	Other building for leisure time purposes
910	Garage with room for one or two cars
920	Carport
930	Outhouse

The registration in the BBR is done on three different levels; property level, building level and units for housing or business. The division is seen in Figure 5. Different information is registered on the different level, but relevant for the heat atlas is the registration of year of construction, size and heat installation on the building level. The building level is also the one used in the heat atlas, meaning that several units can be represented by one registration in the heat atlas. The implementation of the registration levels happened when the BBR was introduced in 1977. [71]

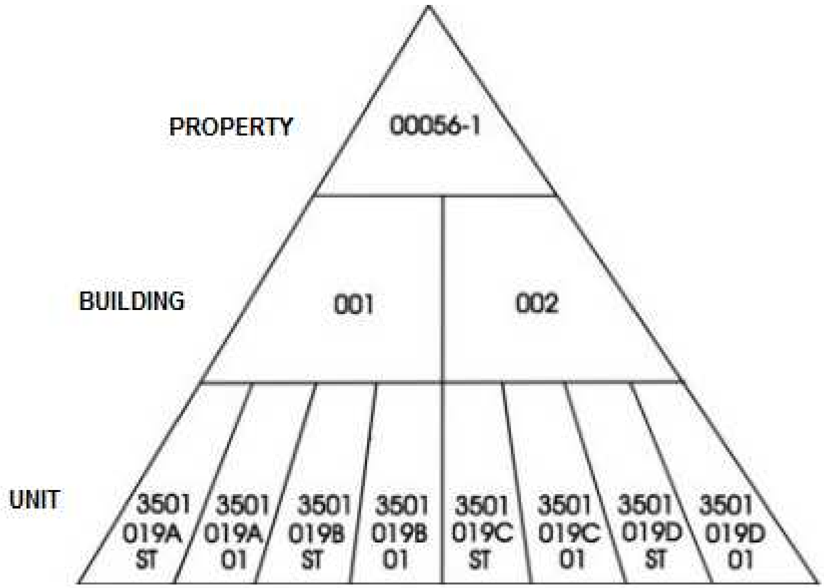

Figure 5: Example of registration levels in the BBR. Adjusted from [73].

By initiating the BBR in 1976 and introducing the building usage codes and a uniform way to register buildings when establishing it in 1977 the methods of working with the data for the Danish Heat Atlas today were enabled. The BBR was not implemented with energy planning as the purpose, but the information contained within has proven useful for energy modeling. This type of detailed data allows for a bottom-up approach to heat planning with the single building as the smallest unit. Up until 2010, the usage of the BBR for heat atlas development was mainly for data on building parameters, The data was related to specific heat demands for building types and age classes and multiplied with registered building areas. Since then a new addition to the BBR was initiated by a new database containing metered or billed energy consumption data for the buildings.

4.2. THE FIE DATABASE

The FIE[6] database was initiated with the implementation of the act for the obligation of energy supply companies to report to the building and housing register[7]. The act was implemented in 2010 and states that energy supply companies supplying district heating, natural gas and fuel oil have to report the end-user consumption to the BBR register. The purpose of the law is to make visible the energy consumption in the buildings. The reporting is following the account settlement structure of the individual energy companies, and all account settlements containing the date 1 January 2010 and thereafter has to be reported to the BBR. [74] Further, in a revision in 2013, electricity consumption is also included in the reporting [75]. This will enable further use cases for the database in energy research. However, in work presented in this thesis only data on heat consumption is used.

The FIE database will over time become a national database on energy consumption for heating purposes and be implemented as part of the BBR. However, currently, the data is accessed independently which also means that it is not fully integrated with the BBR and does not contain unique identification or link to specific buildings. The current data structure contains information about the address for the heat delivery divided into several database table fields containing information on individual parts of the address such as zip code, municipality number, road code, house number, and letter. These columns are combined to form a unique code to merge the data with the BBR data using a similar approach for the BBR information. Unfortunately, this method cannot ensure a complete one-to-one match of all heating data with individual buildings and some data is therefore not useful in the further analysis of heat consumption. This is often caused by one metering unit being shared by several buildings or housing units. It is not possible to allocate the heat demand to the individual buildings or housing units, and the data is therefore not useful for the further analysis. The reason for these difficulties in merging the FIE data with the BBR is that heat metering does not take place at a specific level in the BBR; in some cases, it is done on the unit level and in others across several properties. Furthermore, it is possible to supply unique address ID or unit ID from the BBR when reporting the metered heat demands but it is not a required information. [76]

Merging the FIE data with BBR information allows for an analysis of the heat consumption in which building characteristic is used. The details of the method used to develop the heat atlas with metered heating data are described in Chapter 6.

---

[6] Forsyningsselskabernes indberetningsmodul for energidata – Supply Companies' Reporting Module for Energy Data

[7] Bekendtgørelse om energiforsyningsselskabernes indberetningspligt til Bygnings- og Boligregistret (BBR)

All data delivered to Aalborg University from the FIE database is covered by a non-disclosure agreement. This means that data for individual buildings cannot be published or directly be a part of any publications. However, it is allowed to use the data for research and in the development of the heat atlas as long as it is not possible to identify the heat consumption of individual buildings.

4.3. MAPPING SERVICES IN DENMARK

Several mapping services containing information on Denmark has been used throughout the work presented in this thesis. The main ones are presented in the following.

PlansystemDK contains spatially explicit information for all plans according to the Planning Act[8][62].Most relevant for heat planning are the heat supply zones for district heating and natural gas which delimit the areas in which buildings may be connected to district heating or natural gas. The supply zones are used in Paper 1 and Paper 2 to delimit the existing zones for district heating and are merged with data on heating prices from the Danish Energy Regulatory Authority[9]. This enables the inclusion of consumer prices of district heating in the analyses done in the papers.

Styrelsen for Dataforsyning og Effektivisering, previously know as Geodatastyrelsen manages mapping services in Denmark. The main access point is the online distributor of maps and geodata Kortforsyningen [44,77]. Through the Kortforsyningen portal, it is possible to find spatially explicit data on for example administrative borders (regions, municipalities and urban zones), buildings and infrastructure. This data is used in Paper 1, Paper 2 and Paper 3. In Paper 1, data on urban zone locations are used to delimit potential district heating areas. In Paper 2, the same approach is used and combined with road networks to enable an estimate of distribution grid costs within potential district heating areas. In Paper 3, mainly administrative borders are used to enable statistical comparison of the heat atlas within Regions, Municipalities, and Urban Zones.

All geodata in both Plansystem DK and Kortforsyningen is public and available free of charge, and can freely be used for the purpose of research. The data available through the online interfaces is the same used by the Danish municipalities for public planning and administration following the same update frequency as for the municipalities. This means that no loss of information or delays in access to new data occurs in the data processing. This enables easy access to geographical data for

[8] Planloven.

[9] Energitilsynet

Denmark and ensures that work with for example the Danish Heat Atlas can easily be put into a geographical context.

4.4. THE DANISH HEAT ATLAS VERSION 4

The Danish Heat Atlas developed by Aalborg University has existed in several versions over the years and has been used in a number of publications. [9] attempts to divide it into five overall versions. Most of the versions have existed in different iterations, but the overall division is based on the age of the BBR data used when generating the heat atlas. In the study performed in Paper 1 and the analysis done in the reports [6,47] version 4 of the heat atlas was used. Version 4 was developed using the BBR register from 2013 as well as indicator numbers for heat consumption per square meter in buildings from the Danish Building Research Institute[10].

The indicator numbers from the Danish Building Research Institute comes from the report [78]. The data is based on energy labelling of approximately 130,000 Danish buildings in connection with sale or rental in the years 2005-2010 and only for residential and service-sector buildings. The report focuses on the potential for energy renovations in the buildings and estimates the cost for three different scenarios with different end-use heat savings. The cost of the renovations are both calculated as direct cost for the renovation and as indirect cost where only the added value for the improvement is included compared to renovation without improvements to the energy performance.

4.5. DATA OUTSIDE OF DENMARK

This section will focus on data and mapping services used for the study in Paper 4, in connection with access to the Flemish Heat Map and the Pan-European Thermal Atlas.

4.5.1. FLEMISH HEAT ATLAS

The Flemish heat atlas is based on data on metered gas and electricity consumption per consumer in 2012. The data originate from the distribution companies EANDIS and Infrax. [4]

The heat demand per consumer is estimated based on their consumption of electricity and natural gas. For consumers with electrical heating, a part of their electricity consumption is assigned for heating withholding another part for normal electricity consumption. In the case of natural gas heating, a share of the gas consumption is

[10] Statens byggeforskningsinstitut (SBi)

deducted for cooking, and the rest is assigned for either space heating or sanitary hot water.

Consumers without electric heating or gas heating are identified based on their electricity bill. They are assumed to use other fuels for heating and are assigned a heat demand weighted according to the electricity consumption on the address. More information on the methods is available in Paper 4.

In the heat atlas, the consumer data is summarized in either 100x100m or 1200x1200m resolution. Due to the protection of privacy of the consumers, only grid cells with more than three consumers are included in the map. For all grid cells in the 100x100m resolution with three or fewer consumers, the heat consumption is not included in the 100x100m resolution map. The heat demand is instead included in the 1200x1200m resolution map but distributed evenly across the full grid cell.

4.5.2. PAN-EUROPEAN THERMAL ATLAS

The Pan-European Thermal Atlas (Peta) is based on national energy statistics combined with statistics on NUTS3-level. The heat demand is distributed spatially as a function of the population, land use and soil sealing. The resolution of the grids, as well as, the year of origin of the different grids are seen in Table 2.

Table 2: Year of origin and resolution of the data for Peta, based on [4].

Data	Resolution	Year
Energy statistics	NUTS3	2010
Population	1000x1000m	2011
Land use	100x100m	2006
Soil sealing	100x100m	2009

The method applied in Peta uses the land cover codes to indicate where the population is located within the 1000x1000m grid. It further uses soil sealing as a proxy for the intensity of the built environment and thereby the population density. The residential heat demand is calculated based on the population number in the 1000x1000m grid but distributed based on the ratio of soil sealing in each of the 100x100m grid cells with land cover codes for settlement. More details on the methods are available in Paper 4.

CHAPTER 5. EXPANSION OF DISTRICT HEATING IN DENMARK

This chapter will focus on the work done investigating the potential of expanding the district heating in Denmark. The main work done in this field during the duration of the Ph.D. is described in [1,6,47]. In Chapter 6, further work done to develop the heat atlas is described including a more advanced distribution grid model and the development of version 5 of the heat atlas.

5.1. USING THE BUILDING LEVEL HEAT ATLAS

The Danish Heat Atlas is a building level heat atlas. This means that the heat demand is estimated for each individual building in Denmark. The building data and location comes from the BBR register, which contains information about, amongst other things, the building type, size and age of all Danish buildings. This information is combined with indicator numbers (national averages) on specific heat demand developed by the Danish Building Research Institute. The output is a heat atlas, which contains information on each individual building.

When using the heat atlas, the building level allows for very detailed analysis of for example the potential of district heating and individual heating. The analysis performed in Paper 1 looks at the potential for district heating in buildings outside of the current district heating areas. Similar analyses were done in the [47] and [6]. Only buildings within urban zones are included in the analyses since district heating in general only makes sense in areas with a high heat demand density. Urban zones in this thesis refer to the Danish administrative unit “bypolygon” from kortforsyningen.dk. The layer contains polygons delimiting all urban zones in Denmark. This means that the layer contains everything from the smallest village to the Capital Copenhagen.

The single building resolution allows the economic analysis of the expansion potential to be calculated based on costs for the individual buildings, such as the branch pipe and the district heating unit. This means that the cost calculations for district heating and the alternative individual heating options are based on data specific to the investigated area and not average costs depending on the heat demand density.

Other parameters are calculated without the single building information. For example, the cost for the distribution network is calculated using information on the area of the urban zones in which the potential is calculated. In Paper 2, the distribution cost calculation is also done using the single building information.

Single building heat atlases allow for very detailed calculations. However, there are also a number of pitfalls, which will be explained in the following.

Having a heat atlas estimating the single building heat demand does not mean that the heat demand of each individual building is known. The estimate is based on aggregated data and hence indicates an average value based on the building characteristics. The actual heat demand is very dependent on a number of factors, such as thermal comfort level of the residents, general user behavior and specific thermal performance of the building. Therefore, the actual heat demand in the individual buildings can have a large variation from the estimate of the heat atlas, sometimes several times larger than estimated. Paper 3 investigates this difference further, by looking at the performance of the heat atlas when compared to actual measurements. This is described in Chapter 6.

Another unknown is the maintenance state of the individual buildings. This is both important when considering the level of insulation, which might have been improved to a higher level than the average for the building type and age. Further, a pre-requirement for many heating options is a water-based heating system inside the building. This is often found in Danish buildings, but buildings heated by electric radiators and some types of biomass-based heating systems do not have this requirement. Changing the heating system in these buildings is, therefore, more expensive, and the number of buildings with this shortcoming is unknown in the analysis. It is expected to be the minority of buildings since only approximately 5 percent of all Danish buildings are heated by an electrical heating system [79].

Thirdly, the economic constraints of the individual owners are unknown. A change in the energy performance or heating system is a costly investment in the building, and the ability to make this investment depends on the economic situation of the building owners. Furthermore, the ability to invest does not guarantee an interest as the owners might have other preferences before investing in the buildings heating system. This can especially be the case when the owner and the user of the building are not the same [80].

The added value of a single building level heat atlas is first and foremost appearing in the economic calculations, which can be more detailed and include the number of buildings and the estimated heat demand of the individual buildings. As Chapter 7 and Paper 4 show, heat demands can also be mapped without single building information, but it leads to more average predictions of heat demands, as well as, more assumptions for the economic calculations.

5.2. CALCULATING THE EXPANSION POTENTIAL OF DISTRICT HEATING USING THE DANISH HEAT ATLAS

Paper 1 is an analysis of the expansion potential of district heating in Denmark depending on economic approach using version 4 of the Danish Heat Atlas as an input for the heat demands in the buildings. The economic calculations are done for both consumer-economy and socio-economy in order to see the differences in results introduced by the difference in the economic approach. The calculation demands both a spatial analysis as well as an economic analysis.

The spatial analysis is used to calculate the input parameters for the economic analysis. Firstly, all urban zones are divided into two groups; the ones currently supplied with district heating and the ones currently not supplied with district heating. The further analysis then focuses on the latter in order to calculate the economic potential of expanding district heating to include these zones.

The paper aims to investigate the potential of expanding the existing district heating networks into neighboring urban zones. The spatial analysis, therefore, calculates the distance from each of the potential new district heating urban zones to the nearest existing district heating area. This distance is used as an input to the economic cost of expanding the transmission grid. The other part of the economic analysis consists of estimating the cost of establishing a distribution grid based on the land area of the urban zone and the cost of installations in the buildings estimated based on the number of buildings within the urban zone. Following this, the cost of heating is assumed the same as in the existing district heating network. All the costs are found for both consumer-economy and socio-economy. Figure 6 shows an example of the spatial calculations.

The socio-economic approach is in line with the Heat Supply Act, stating that the most socio-economic beneficial heating solution has to be installed [45]. It is therefore similar to the approach used when public authorities investigate district heating potentials. The consumer-economic approach instead aims at estimating the cost of district heating for the consumers. For both economic approaches, the cost of both district heating and alternatives are determined. The study is, therefore, able to analyze whether the consumer-economic costs incentivizes the consumers to choose the socio-economic most beneficial heating option.

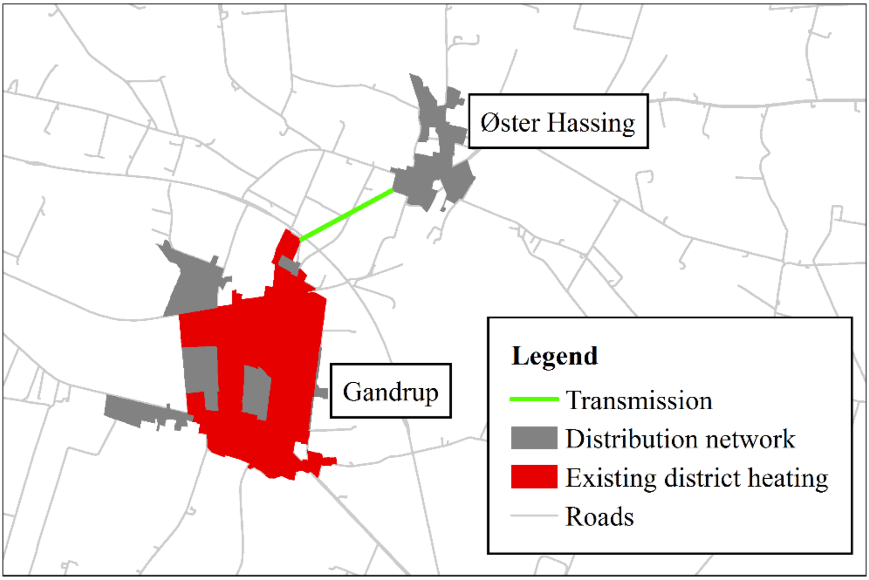

Figure 6: Example of spatial calculations for the Gandrup-Øster Hassing area in Northern Jutland, Denmark. Distribution costs are calculated for the grey areas, the green line illustrates the estimated transmission line, and red areas are the current district heating areas from which the district heating cost is taken. The Figure is from [1].

5.3. ECONOMIC APPROACHES TO HEAT PLANNING

The economic approach to heat planning has an impact on the outcome of the analysis, as highlighted in Paper 1. The results of the paper are only valid in a Danish setting since they are sensitive to the specific tax scheme, but similar differences to the potential of district heating are likely to appear in other countries as well.

The paper aims at highlighting how different economic approached results in different potentials for district heating. The analysis calculates the cost of implementing district heating for urban zones using both a socio-economic approach and a consumer-economic approach.

5.3.1. SOCIO-ECONOMIC APPROACH

In Denmark, heat planning is typically taking a starting point in socio-economic calculations. This is related to the Danish heat supply act, which states that the purpose of the law is to promote the most socio-economic and environmentally friendly utilization of energy for heating purposes. The socio-economic approach is intended to ensure that only socio-economic beneficial heating options are permitted in Denmark. [45] In Denmark socio-economic calculations means that the costs are calculated without VAT and taxes and with a specified interest rate, currently at 4%.

Furthermore, in the case of district heating, the calculations are done without accounting for profit, which is due to district heating having to be non-profit in Denmark and therefore only are allowed to charge the consumers the actual costs of producing the heating and operating the network and company. [45]

When doing socio-economic calculations on heating options, the cost of the investment in heating equipment and fuel is based on socio-economic costs. This means that the investment and fuel costs are without VAT and other taxes. The fuel costs in Denmark are based on [81] and reflects the cost for the Danish society consuming the fuels. The investment costs are in the study based on [82,83] and reflect a reasonable cost for the different heating options.

However, knowing the socio-economic potential of district heating is not necessarily enough to ensure the implementation of this amount of district heating. The choice of heating option in the individual buildings is with the owner of the building. It is possible by law to make district heating connection mandatory for buildings within certain areas following [48]. The implementation of the law is done in the city councils of the Danish municipalities, but there is a certain hesitation in applying it. Firstly, forcing owners to specific heating options is a drastic political decision, which can meet a high level of local resistance. This, of course, can have an impact on the political will to use the option. Further, buildings meeting newer building standards in Denmark are by law exempted from the requirements if they choose to apply for it. Therefore, the choice of heating is in many cases solely taken by the owners of the buildings, and it is assumed that the cost of heating has a large impact on this decision.

5.3.2. CONSUMER-ECONOMIC APPROACH

Calculating the consumer economy of different heating options helps to identify areas where district heating is both the socio-economically best option and where it also reduces costs for the consumers.

The consumer-economic calculation aims to investigate the actual heating cost for the consumers, including the investment and fuel costs. Further, the current tax schemes for fuels are included in the calculation to reflect the consumer price of these. It is assumed that the consumers are most likely to choose the cheapest heating option. The heating costs used in the consumer-economic calculations are based on local district heating prices from the nearest district heating supply area from [84] and for the alternative heating options [85] is used as a guideline.

Other parameters not included in the study can also affect the choice of heating option for the owners of the buildings. For example, the ease of use of the different options is very different, where natural gas and district heating generally requires very little interaction to get the heat other options like biomass are more time demanding and requires regular work to clean and maintain the equipment and supply the fuel to the burner. Similarly, the local air pollution effect is different between the different options. Again, the biomass is likely to be the worst option with a relatively high local pollution impact due to the smoke from the chimney.

5.3.3. RESULTING DISTRICT HEATING EXPANSION POTENTIAL

The economic benefit of district heating in different areas depends on the economic approach applied. The expansion potential for district heating at a lower cost than all alternatives is approximately 13% of the total Danish heat demand for the socio-economic approach. The corresponding number is only 9% for the consumer-economic approach. Even though the calculations are done for the same areas with the same consumers and grids, the areas included in the 13% and 9% respectively do not fully overlap. This means that in areas where district heating is socio-economic feasible it is not necessarily also consumer-economic feasible but in other areas it can be consumer-economic feasible but not socio-economic feasible. District heating is the heating option with the lowest cost in both economic approaches in 6% of the total Danish heat demand.

This means that 7% district heating potential is socio-economically viable but not able to compete with the alternatives when looking at the economy for the consumers. A similar situation is seen in some areas where the consumer-economy is better for district heating than the socio-economy. The reason for this is found in the Danish tax regulations, in which biomass is almost exempt from taxes. The mix of production units in the district heating networks has a large impact, and networks with a high share of biomass are better able to compete with the individual alternatives in the consumer economic scenario. When looking at socio-economic calculations biomass has a high cost for the society, and some of the same areas are therefore not able to compete with the socio-economic cost of the alternative heating options.

Overall, the expansion potential for district heating is only present in relatively dense urban areas, which are located in close proximity to existing district heating networks. Two main factors have an effect on the potential in the individual urban areas. Firstly, the heat demand density, which affects the cost of the distribution grid per delivered unit of heat. Secondly, the distance to the closest existing district heating network, which affects the transmission grid costs. Both these factors are geographically bound, and an analysis of the district heating potential is dependent on geographical knowledge of the area in question.

The heating price also has a high impact on the competitiveness of district heating, and by using the cost of the nearest district heating network, this cost also becomes geographically bound in the analysis. The heating price of district heating is a result of the non-profit regulation of district heating in Denmark, and further a result of the production units and fuel types used in the individual district heating networks. The parameters determining the cost of heating in the district heating networks has not been a part of the study.

5.4. BENEFITS AND CHALLENGES OF A SINGLE-BUILDING HEAT ATLAS

The main benefit of a building scale heat atlas is the option to include the location and characteristic of the individual buildings in for example economic calculations. In Paper 1, this is done by including the number of buildings and their expected heat consumption when calculating the size of the transmission grid and the number of district heating units.

A challenge with a single-building heat atlas is that although it estimates the heat consumption of each individual building, it is not accurate on a single building level. Consequently, the calculations done in Paper 1 are considered a screening of the expansion potential and not an accurate account to where district heating should be implemented in Denmark.

Finally, this type of estimates of district heating potential is almost impossible to do in many countries, while most countries would require a completely different methodological approach. The detailed information needed for each building together with knowledge of typical heat consumption in different building types often does not exist on a national level. This makes the types of studies done in Denmark very difficult to directly replicate in other countries. Therefore, other ways of estimating the heat demand density and the costs of district heating can be necessary.

CHAPTER 6. FURTHER DEVELOPMENT OF THE DANISH HEAT ATLAS

An ongoing process to improve the Danish Heat Atlas has been taking place over the years. As described in Chapter 5, the fourth version of the heat atlas was used during the initial studies of district heating expansion potential in Denmark. In the following the developments in the fifth version of the heat atlas is described together with a more detailed model to estimate district heating and low-temperature district heating potentials. Further, an analysis of the accuracy of the newest version of the heat atlas is done comparing it to measured heat demand in individual buildings.

6.1. DANISH HEAT ATLAS VERSION 5

The fifth version of the Danish Heat Atlas is more than just an updated version of the previous edition. The methodological approach to developing the indicator numbers for the heat demand in buildings has been changed completely. In all previous versions, the heat demand indicator numbers have been taken from the Danish Building Research Institutes values to predict heat demand in buildings. In the newest version, these numbers are replaced with indicator numbers generated from statistical analysis of actual heat demand in Danish buildings.

The measured values of actual heat demand come from the FIE dataset as described in Section 4.2, in which all district heating, natural gas, and fuel oil providers have to report the consumption data for their consumers. This has a background in the act for the obligation of energy supply companies to report to the building and housing register from 2010 [74]. The reporting is therefore still incomplete and has been an ongoing process with data collected for building in Denmark for all years since 2010. In the current version of the heat atlas data collected until 2014 is used. Table 3 and shows the number of buildings with registered heat demand in the different years.

Table 3: Frequency of measurements categorized by heat supply and building type [2].

	2010	2011	2012	2013	2014
District Heating	562,718	599,037	579,537	616,873	533,568
Natural Gas	355,461	357,662	361,548	362,783	313,854
Oil	161,982	162,396	153,720	106,458	46,315
Total	1,080,161	1,119,095	1,094,805	1,086,141	893,755

The availability of actual measured heat data raises the question if a heat atlas still has relevance. Several reasons justify the efforts in the development of the current edition of the heat atlas and the continued development of future heat atlases. Although data on the actual consumption exists for more than one million buildings, see Table 3, this leaves a larger number of buildings without measurements. It is predicted that the FIE database will have a higher coverage in the future with an expectation of approximately 80% of all buildings included [86], however, it is not expected that it will ever reach a coverage of 100%. A heat atlas is able to use the collected data on actual heat consumption in a generalized method to create indicator numbers for all Danish buildings. This enables an estimation of heat consumption for all buildings and enables heat planning for buildings where measured data do not exist. At present, it is not possible to use measured values for the buildings where they exist and estimated values for buildings without measurements. This is due to the protection of the privacy of the consumers.

A further benefit of a heat atlas is that the estimated heat consumption in the individual buildings is based on building characteristics rather than user behavior. Where the collected data in the FIE database is confidential and therefore restricted in its use, the heat atlas has no such restrictions and can be freely used in research projects. It further represents an average heat demand value based on the characteristics of the building and is therefore not depending on the occupant of the building, which is likely to change over time. In future iterations of the heat atlas demographic indicators might also be used to increase the accuracy of the estimated heat demand but the user behavior of the inhabitants of the building will not be directly predicted. This, of course, is also a shortcoming of the heat atlas, which will never be able to predict heat demand for each individual building accurately.

6.1.1. THE FIE DATA

The input to the calculation of the indicator numbers for the fifth version of the heat atlas is the measured heat demand values from the FIE data described in Section 4.2. Before the FIE data is made available to the researchers, it is climate corrected to account for the difference in heat demand due to climatic differences between the years. Further, a first sorting of the data is done to remove some of the errors which are prone to occur when collecting such large amounts of data. However, especially in the first editions of the data several errors were still present which led to the removal of several hundred thousand buildings from the data set. One of the obvious errors were, for example, the presence of more than 100.000 buildings registered to have been built before the year 1600 even though that many buildings from pre-1600 does not exist in Denmark. Since it was not possible to determine the correct construction year of the buildings, which is needed to generate the indicator numbers, the only option was to remove all of this data from the analysis.

A more complicated clean-up issue is that some buildings have unrealistic high or low heat demands. Low heat demands can, of course, be explained with the buildings being periodically uninhabited. However, the heat atlas needs to estimate the heat demand of buildings in use in order to estimate the correct load on a district heating network and the correct size of district heating pipes. For the large heat demand, some single-family buildings have demands registers of more than 1 GWh per year, which with a normal installation is not possible. Due to these challenges, it was chosen to maintain the division into age categories from the previous heat atlases since it follows the implementation of building regulations in Denmark. Similarly, the building types according to the BBR register are used to split the data into different groups. This enables the usage of the previous version of the heat atlas as a guideline to realistic heat demands in the buildings.

The total heat demand of the buildings was transformed into a heat demand per square meter. It was chosen to remove buildings with a heat demand of more than six times the expected heat demand, or more than four times and above 200 kWh per square meter. For the low heat demands, buildings with a consumption of less than one quarter of the expected heat demand were also removed. This process removes the majority of outliers from the dataset but has the downside that it might also remove data, which is correct. It still maintained a very high number of data available for further analysis, and it is expected that the amount of correct data removed is far smaller than the amount of erroneous data. The limiting values for removal of data are chosen to remove the buildings with the most extreme values, with a special focus on buildings with unrealistic high heat demands. This method is chosen rather than for example the 5% highest and lowest values since the data is not normally distributed, but rather skewed towards higher values. Therefore, the aim was to remove the most extreme values, based on previously predicted values for heat demand in the building categories.

The processing of the FIE database into the categories used in the statistics is seen in Figure 7. The total number of values is split based on BBR category and following this based on the age of the buildings.

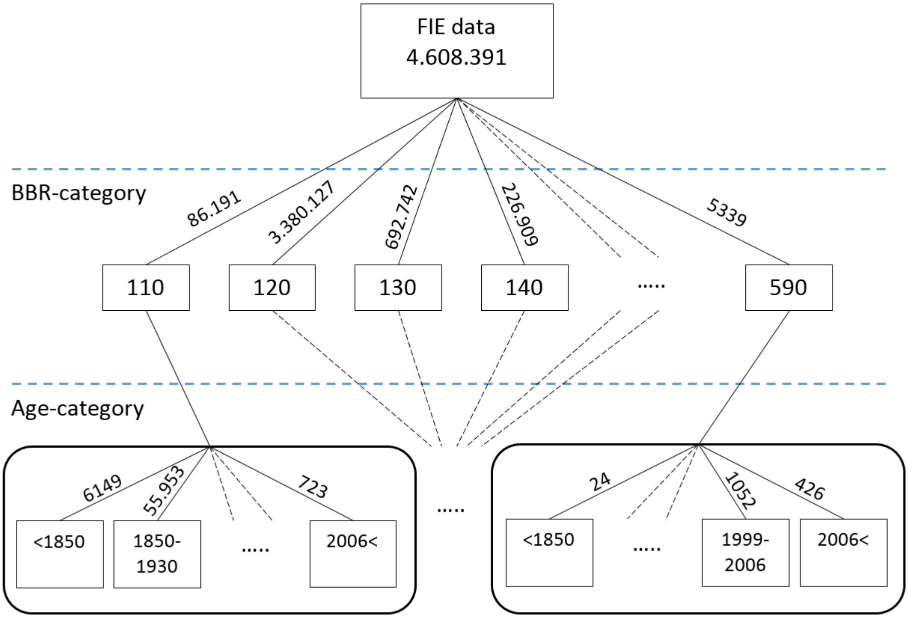

Figure 7: The process of dividing the FIE database into categories based on building type and age. The numbers show the number of buildings in each step, corresponding to the numbers in Table 4.

The number of input values in each of the BBR and age categories varies largely, with parts of the residential sector having several thousand in each category other categories have very few buildings for the statistical work, see Table 4 and Figure 8. Even though some categories have a low number of buildings, the statistical analysis is done on all categories except BBR540, in which the number of buildings is too low for any statistics.

Table 4: Number of buildings per type and age category [7,9].

	<1850	**1850-1930**	**1931-1950**	**1951-1960**	**1961-1972**	**1973-1978**	**1979-1998**	**1999-2006**	**2006<**
BBR110	6149	55953	9196	3397	3815	2711	3024	1223	723
BBR120	31815	513208	375743	346955	971929	488983	374046	169003	108445
BBR130	9446	84597	50209	44183	90229	61391	212719	86888	53080
BBR140	5948	131003	47371	9466	9438	2432	11155	6506	3590
BBR150	36	267	82	75	419	80	589	164	138
BBR160	60	945	388	381	696	430	1307	857	389
BBR190	52	598	138	85	148	56	199	73	33
BBR210	109	1259	484	443	907	380	329	197	93
BBR220	167	2972	2419	3005	9810	5432	11100	3051	1345
BBR230	0	75	56	120	258	65	269	64	65

BBR290	7	96	52	36	55	62	254	93	82
BBR310	5	252	146	212	466	289	890	248	155
BBR320	3280	25745	6259	4807	12385	6244	14276	6470	4656
BBR330	785	6196	1150	941	1770	632	1974	544	322
BBR390	12	135	81	44	161	101	349	154	80
BBR410	631	4585	905	662	995	489	1528	454	278
BBR420	176	2450	788	1079	1549	587	1246	502	237
BBR430	21	451	174	134	418	278	301	162	99
BBR440	69	2188	1089	970	3355	1262	4320	1323	442
BBR490	12	623	219	181	247	94	348	212	91
BBR510	467	2067	1064	760	2507	999	1110	1377	5046
BBR520	20	277	102	81	144	83	117	27	11
BBR530	25	529	506	535	1459	1019	1718	402	263
BBR540	0	0	6	2	3	0	1	17	3
BBR590	24	773	296	186	414	144	2024	1052	426

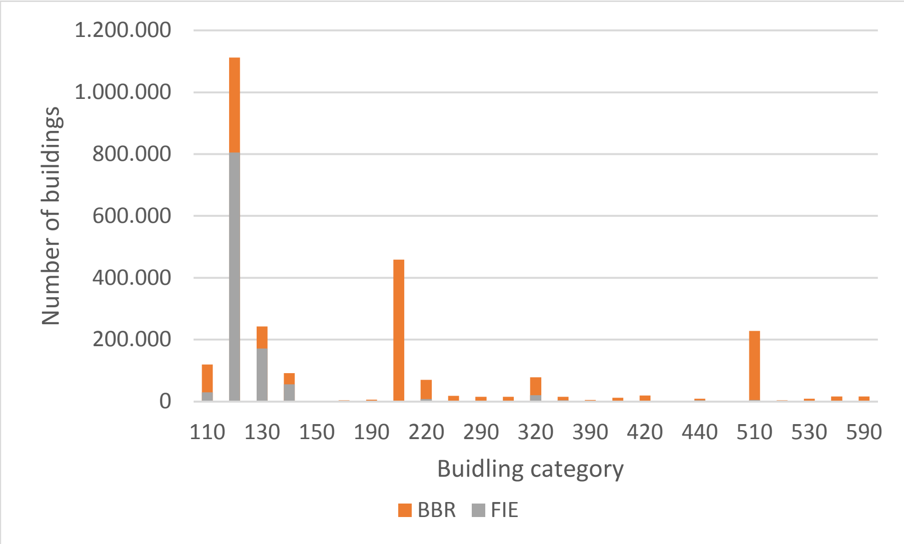

Figure 8: Number of buildings with measurements (FIE) compared to the actual number of buildings in Denmark (BBR). [3]

The heat demand per square meter for the buildings generally follow a similar pattern across the building types with a slowly increasing heat demand per square meter until the early/mid-nineteen hundreds followed by a more rapid and continuous decrease in heat demand per square meter for newer buildings. Examples are BBR120 (detached single-family houses) and BBR220 (Commercial production regarding industry, trades a.o.) as seen in Figure 9. The majority of BBR categories show similar tendencies although a few of the categories with very few buildings are less ordered.

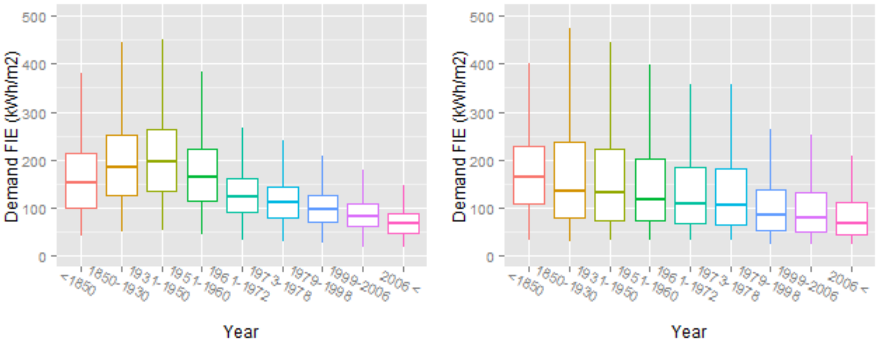

Figure 9: Left: BBR120 (detached single-family houses), Right: BBR220 (Commercial production regarding industry, trades, a.o. (Factory, workshop a.o.)). Heat consumption per m2 depending on the age of the buildings [7,9].

The result of work with the FIE database is an indicator number for the heat demand per square meter of floor area in the Danish buildings based on the BBR category and the age of the buildings. The indicator numbers for all categories are seen in Table 5. This information is then combined with the BBR register information for all Danish buildings, and the estimated heat demand is calculated for each building and is available geographically explicit to be used for further analysis using GIS.

Table 5: Annual heat demand in kWh/m^2 by building usage code and construction period [7,9].

	<1850	**1850-1930**	**1931-1950**	**1951-1960**	**1961-1972**	**1973-1978**	**1979-1998**	**1999-2006**	**2007<**
BBR110	137	156	173	179	138	126	115	106	82
BBR120	152	185	197	163	123	110	97	82	65
BBR130	170	180	192	172	130	112	80	69	67
BBR140	143	139	144	148	117	116	84	76	68
BBR150	182	177	164	141	128	180	122	111	86
BBR160	249	206	171	186	153	143	125	112	82
BBR190	142	172	196	155	151	131	106	74	83
BBR210	215	244	235	190	198	192	157	166	148
BBR220	183	171	163	151	142	141	107	103	94
BBR230	195	195	104	104	171	184	145	227	164
BBR290	211	185	184	161	138	183	105	132	72
BBR310	200	178	211	204	176	121	112	119	101
BBR320	124	125	153	144	125	114	95	75	55
BBR330	215	175	170	152	182	149	135	146	117

BBR390	102	121	140	162	113	197	128	99	134
BBR410	182	162	163	156	150	138	121	116	123
BBR420	253	231	233	244	173	163	130	114	102
BBR430	363	237	220	249	161	152	133	148	130
BBR440	256	243	233	216	168	157	125	116	96
BBR490	167	177	201	158	187	155	113	136	78
BBR510	94	107	106	98	101	100	71	73	69
BBR520	167	200	211	164	153	135	131	106	174
BBR530	163	141	127	142	133	131	115	130	124
BBR540	0	0	0	0	0	0	0	0	0
BBR590	116	107	99	104	97	108	69	68	58

6.2. ONLINE ACCESS TO THE HEAT ATLAS

Data has more value if it is available for usage. Therefore, it was decided to make an aggregated version of the heat atlas available online through [8]. As a small precaution in the first edition of the online interface, the full level of detail of the heat atlas is not available. Instead, the heat demand along with the number of buildings is summarized on urban zones, municipalities, regions and all of Denmark.

The heat atlas is made available as an online map with OpenLayers 3 [87], enabling a point-and-click interface similar to that found in many other mapping applications online. The layer(s) of interest can be chosen, and detailed information is available by clicking, e.g., an urban zone of interest. Currently, the available information is the number of buildings and heat demand. The heat demand is displayed as total heat demand and further divided into overall building categories and according to heat supply type.

Together with the estimated heat demand the sum of measured heat demand from the FIE data is also displayed on the web page for all categories containing more than five buildings. Categories with fewer buildings are not displayed in order to protect the privacy of the consumers. Displaying the FIE data enables an insight in the number of measurements in different parts of Denmark.

6.3. FURTHER DEVELOPMENT IN USE CASES

Together with the development of the newest version of the Danish Heat Atlas improvements are also done for the application in the economic calculations of the district heating potential.

In Chapter 5, the economic calculations consist of estimated costs for consumer connections based on the number of buildings within an urban zone, an estimate of the cost of the distribution grid based on the size of the urban zone and an estimated cost of the transmission grid based on the distance to the nearest existing district heating grid. All of these costs come with some uncertainty, but especially the method used to estimate the cost of the distribution grid adds a big uncertainty to the overall cost of implementing district heating. The size of urban zones is to some extent correlated with the number of buildings within the zone [88]. However, the boundary of the zone does not necessarily follow the build-up area closely but can expand further out. Further, in many urban zones, a substantial part of the zone is allocated for other purposes than buildings and therefore does not need a distribution grid.

The actual cost of a distribution grid is closely correlated with the mutual distance between the buildings together with the number of buildings within an urban zone. Therefore, a new method to estimate the cost of the distribution grid is developed and presented in Paper 2.

6.3.1. DISTRIBUTION GRID COST

The novel method of calculating the cost of the distribution grid presented here approaches a more real-life scenario taking into account the spatial location of the individual buildings and assuming that the pipes will follow the road network.

The approach for the calculation starts by selecting all urban zones outside existing district heating networks as potential expansion areas for the district heating. For each of these urban zones, a layout for a distribution grid is calculated. Firstly, the central point of the urban zone is identified and assumed the central connection point of the distribution grid. The function ‘Feature To Point’ in ArcMap is used with the condition that the point has to be inside the polygon of the urban zone. Following this, a network analysis is done to find the shortest route along the road network from each individual building to the central point of the urban zone. The heat demand of the buildings are copied to the routes, and overlapping routes are added together. This information allows for an estimate of the pipe diameters and a calculation of the expected heat losses in the distribution grid. The calculation of pipe diameters and heat losses is able to take into account the temperatures in the grid and reflect the operational conditions of the district heating network.

The rest of the economic estimates in Paper 2 follow the same approach as explained in Chapter 5 and Paper 1. The cost of the transmission grid is still estimated based on the distance to the nearest district heating grid, however, now from the central point to which all individual buildings are connected. For the individual buildings, a standard cost of connecting to the distribution grid is assumed.

With the new approach to estimate the cost of the distribution grid the costs should better reflect the real-world conditions. Further, it is possible to calculate the consequences of different operation temperatures both in regards to the capacity of the pipes and therefore the needed dimension in the network and in regards to the losses in the network.

6.3.2. LOW-TEMPERATURE DISTRICT HEATING

Knowing the layout of the distribution grid together with the heat demand for each part of the network allows for more a detailed calculation of the consequences for the pipes. Two main factors are taken into account; the dimension of the pipes based on the needed capacity and the heat loss in the pipes. The temperature of the water is the main influential parameter for both factors.

In the scenarios in Paper 2, two different sets of temperatures were used. The first one is representing a conventional district heating setup with a forward temperature of 80 °C and a return temperature of 40 °C, resulting in a temperature difference of 40 °C. The second temperature set is representing a low-temperature district heating setup with a forward temperature of 55 °C and a return temperature of 25 °C, resulting in a temperature difference of 30 °C and therefore a lower capacity in pipes of similar dimensions to the conventional district heating setup.

The heat loss is calculated per meter of pipe as a function of the forward and return temperatures in the pipe and the ground temperature. In Paper 2, it results in a lower heat loss for the low-temperature scenario compared to the conventional scenario.

In Paper 2, conventional and low-temperature scenarios are compared assuming 50% heat savings for space heating compared to the present. The comparison is made without other changes to the district heating network. This means that the other benefits of a lower temperature in the district heating network are not reflected in the calculations. Even so, the low-temperature district heating scenario results in a better economy for the potential expansion areas compared to conventional district heating supplying the same heat demand. The added cost of sometimes needing bigger dimensions in the pipes to ensure enough capacity is counterbalanced by the lower heat loss and resulting in a lower cost per delivered heat unit over the lifetime of the system.

In the paper, a scenario with conventional district heating and no heat savings is also analyzed. Compared to this scenario the low-temperature district heating with heat savings has a smaller expansion potential. However, the low-temperature district heating has many benefits which are not included in the calculations and which could result in lower heating prices in the heat savings scenarios. One of the benefits is a higher flexibility in the production units and easier integration of waste heat sources as lower temperatures [40]. Therefore, a direct comparison between the conventional district heating and no heat savings and low-temperature district heating with heat savings is not possible within the boundaries of the study in Paper 2.

With the knowledge developed in Paper 3, on the accuracy of the heat atlas, it will further be possible to make sensitivity analysis of the results based on the parameters of each of the urban zones. This option should be included in future studies on the expansion potential of district heating.

6.4. ACCURACY AND RESOLUTION OF THE HEAT ATLAS

With the new heat atlas being developed based on actual heat demands of Danish buildings it is also possible to test the accuracy of the heat atlas in a new way. The performance of the heat atlas can be analyzed down to the single building level for all buildings where measurements of the heat demand exist. This makes it possible to not only validate the heat atlas on a national or regional level but to test the performance of any number of buildings and within the different building types. This type of analysis is initiated in Paper 3 and will be further elaborated in this section.

The accuracy of the heat atlas is considered as the ability of the heat atlas to estimate the actual consumption of the buildings. However, the heat atlas is not aimed at accurately estimate the heat demand of the single buildings. The heat atlas is developed to estimate the average per square meter consumption depending on building type and age. Because of this, it is expected that individual buildings can have a relatively large deviation from the estimated value of the heat atlas. For larger groups of buildings, however, the heat atlas is expected to estimate heat demands closer to the metered values.

The first check of the accuracy of the Danish Heat Atlas version 5 is on the regional and municipal level, where it is seen that the heat atlas on this level mostly manages to estimate heat demands close to the measured values, see Figure 10. It does; however, seem to have problems predicting the heat demand accurately in Copenhagen and on the north-east of Zealand. The regional analysis shows that the heat atlas in all regions except the Capital Region of Denmark is within a few percent of the measured heat demand. However, in the Capital Region of Denmark, the accuracy is only 89%. Similarly, for the municipal analysis, many of the municipalities within the Capital Region of Denmark show an inaccuracy higher than 10%. In the rest of Denmark, this only applies to a few municipalities.

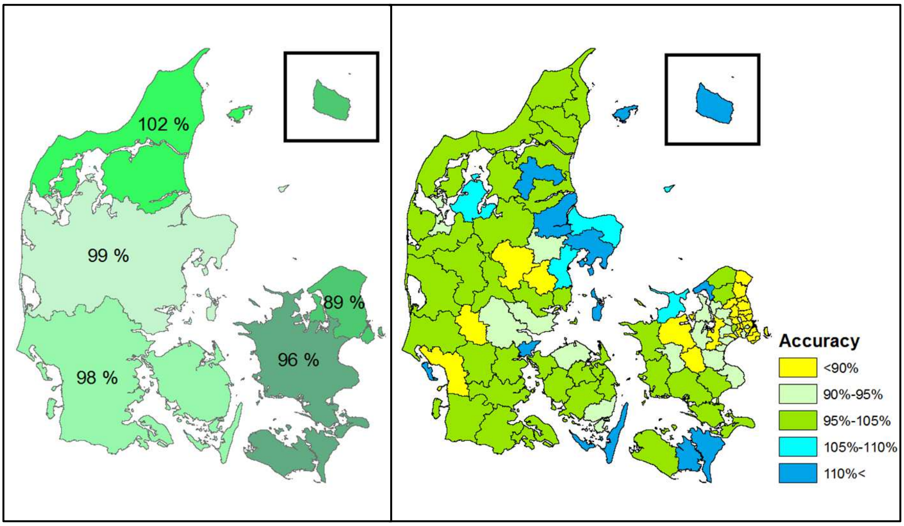

Figure 10: Accuracy displayed geographically in the regions and municipalities of Denmark [3].

Part of the reason for this higher inaccuracy is likely due to the mix of buildings in the different municipalities. The northernmost part of Denmark, the North Denmark Region, with an accuracy of 102% has a similarly high accuracy in the individual municipalities with almost all within 5%. In the North Denmark Region, 80% of the residential buildings are detached single-family houses. 15% of the residential buildings in Region Nordjylland are terrace houses, or multistory buildings and the last 5% are farmhouses. For the Capital Region of Denmark, which has the lowest accuracy, the distribution is 69% detached single-family houses, 1% farmhouses and 30% terrace-houses or multistory-buildings. This leads to investigating the accuracy across the different building types.

Overall, the accuracy is very dependent on the number of buildings included in the sample. Figure 11 shows the accuracy for all Danish urban zones with more than ten buildings with a measured heat demand value as a function of the number of buildings. Many outliers are found with relatively high inaccuracies, but generally, the tendency is a higher accuracy when more buildings are included in the sample.

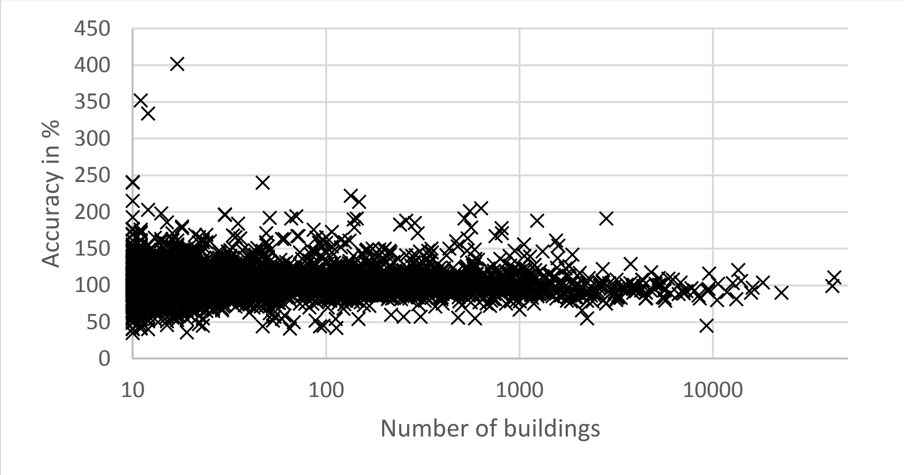

Figure 11: Accuracy in urban zones sorted according to the number of buildings with measured values [3].

Random samples of buildings are also extracted using the sample function in Rstudio. A set number of buildings are extracted from the dataset, either from all available buildings or from one of the building categories at a time. The estimated heat demand is compared to the metered heat demand of the buildings, and the process is repeated 5000 times to generate a boxplot of the results. A similar trend to the ones seen in the urban zones appear when looking at random samples of buildings across all BBR categories, see Figure 12 left. Overall, the majority of predictions are approaching one but with many outliers present due to wrong predictions. Even with 500 buildings in the sample inaccuracies of more than a factor of two occur. If looking at BBR120 only, the detached single-family houses, a much better prediction is seen. Firstly, the majority of predictions are much closer to 1 already with 100 buildings. Secondly, the outliers are fewer and with a much smaller spread from 1.

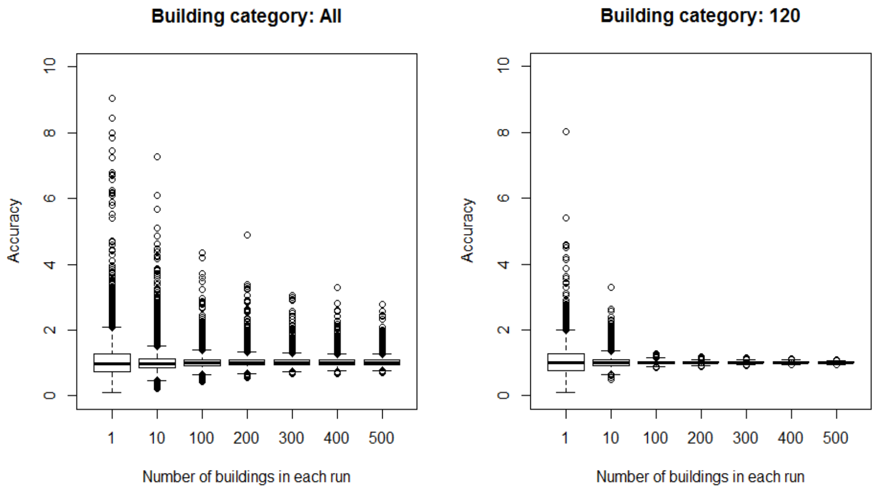

Figure 12: Accuracy depending on number of buildings. Left: All building codes. Right: Detached single-family houses. [3]

Figure 13 shows the corresponding prediction for 500 buildings across all BBR categories. A value of 1 means that the heat atlas estimates the same heat demand for the buildings as the measured value, higher values means that the heat atlas overestimates the heat demand. It is clear that apart from BBR120 (detached single-family houses), many of the other categories are either on average predicted higher or lower than the measurements and many of them have outliers far from the measured value. Therefore, the accuracy of the heat atlas will naturally also be better in areas with many detached-single family buildings and worse off when the mix of buildings contain many from other categories.

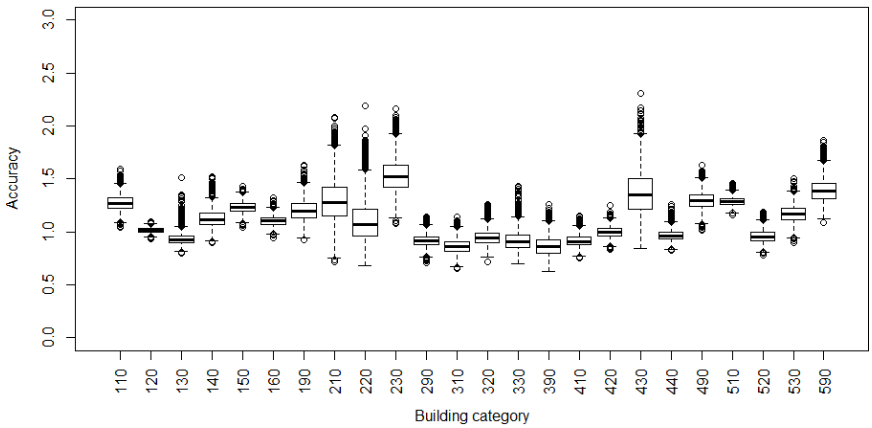

Figure 13: Accuracy for all buildings categories with 500 random buildings [3].

Overall, the accuracy is only fully satisfying for BBR120 (detached single-family houses), where all other categories are either on average predicting some percent too high or low or having too many outliers far from the expected value. This knowledge is important for two reasons. Firstly, it puts the focus on further improvement of the accuracy on BBR categories with low accuracy in the current version of the heat atlas. It also highlights that a generalized method as the one used in the Danish Heat Atlas works well-defined building types but less so for building categories with a larger variation in the building stock. Secondly, it enables the user of the heat atlas to take this information into account. This means that sensitivity analyses should be done according to the number of buildings and the categories they belong to.

With the low coverage of measured heat demands in some BBR categories, as seen in Table 5, and with the very broad range of building types included in many of the categories, see Table 1, it is not likely that a good accuracy can be obtained for all building types. Further work should be done on improving the accuracy where possible, but just as important is to use the knowledge of the accuracy in future studies and acknowledge that for some buildings the heat demand estimate will be linked with a very high inaccuracy. It is possible to mitigate this to some extent by large samples of buildings, but as seen in Figure 10 the accuracy can suffer substantially even for a full region or municipality depending on the mix of buildings.

Another way to use the knowledge when looking at specific areas for district heating is to acknowledge that the accuracy is fairly good for detached single-family houses and then focus on gaining more knowledge on the actual consumption in the remaining buildings. In a small village or town, the majority of buildings are likely to be detached single-family houses and time and energy can then be directed at collecting further information on the remaining buildings.

CHAPTER 7. DISTRICT HEATING OUTSIDE DENMARK

District heating has for many years been a substantial part of the Danish energy system with a coverage of around half of the heat demand and currently 64% of all households [89]. However, in most other countries across Europe and the rest of the world this is not the case. Figure 14 shows the implementation of district heating in the member states of the European Union. There is a clear tendency of a larger implementation of district heating in the northern and eastern European countries. In recent years, through research in the potential of district heating in Europe, more focus has been paid to the potential of district heating in also the central and southern European countries.

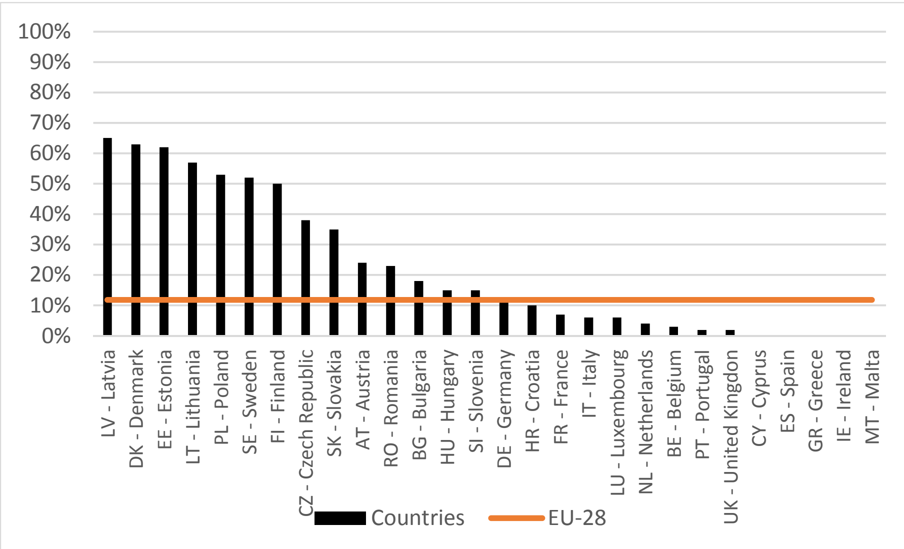

Figure 14: Percentage of citizens served by district heating in the European Union [90].

7.1. DEVELOPMENTS IN OTHER COUNTRIES

District heating was not on the agenda for the future energy system in the European Union until relatively few years ago [91]. This is seen in the fact that the Energy Roadmap 2050 published by the European Commission did not include a thorough analysis of the heating and cooling sector [92], furthermore the first heating and cooling strategy for the European Union was not proposed by the commission until February 2016, following plans for the strategy launched in 2015 [93]. The proposed future before the heating and cooling strategy had a very strong emphasis on electrifying as much of the energy system as possible. This would lead to massive investments in upgrading the electricity grid and production units. Several researchers and organizations even proposed to establish so-called super grids, able to transport large amounts of electricity across the European continent or even as far as from the Sahara desert [94].

In recent years, changes have happened in the perception of the future European energy system. One of these changes is a stronger focus on district heating. Some of the first studies done on a European scale for the implementation of district heating were the Heat Roadmap Europe Pre-studies [92,95]. These suggested the possibility to use district heating as a mean to ensure a high share of renewable energy in the heating sector at a lower cost than with an electrically based heating sector. At the same time, they also suggest integration across the heating and electricity sectors which can help to implement fluctuating renewables in the electricity system without the need for large-scale electrical storage. Another important point made by the Heat Roadmap Europe studies was the vast amounts of excess heat available which through district heating can be used to cover a substantial part of the European heating needs and thereby save fuels and emission.

These studies and others that followed highlighted the possibility of implementing district heating across Europe. Further, in the Heat Roadmap Europe 3 STRATEGO study it was found that district heating is not only feasible in a Scandinavian setting or in cold climates, but could also be implemented in southern parts of Europe [96]. Politically this has led to a new focus in the European energy policy where district heating can be expected to form part of the future energy system. Many other research projects study the implementation of district heating across Europe, for example, the continuation of the first Heat Roadmap Europe Studies in Heat Roadmap Europe 4 [97]. Other examples are of projects doing heat mapping are THERMOS [98], focusing on address-level energy system maps, Hotmaps [99] with a focus on open source mapping and planning tool for heating and cooling and PLANHEAT [100] working on mapping forecasted demands for heating and cooling. The biggest challenge today is therefore not to prove the feasibility of district heating but to ensure the implementation of the technology.

The change in focus in European energy policy is also reflected in the EU regulations. One important implementation has been the Article 14 of the 2012 Energy Efficiency Directive set by the European Commission which states that all member states are obligated to produce maps of the national potential of district heating [101]. Further, a European heating and cooling strategy have been implemented with a strong focus on co-production and the benefits of district heating and cooling [102]. This has led to many maps of the district heating potential across Europe. Heat mapping and heat atlases have been present across Europe for a longer period of time, and many projects initiated work with district heating many years ago. However, in the context of the European Union, the focus on district heating was initiated relatively recent.

With the focus on mapping of heat demands and potentials for district heating, the methodological approaches and their differences become important. A special concern is the comparability between maps developed in different countries and based on different data sources.

7.2. HEAT MAPPING METHODOLOGIES

Overall, it is possible to distinguish between bottom-up and top-down models for heat mapping. Bottom-up models are often more data intensive as they require data on the level of the highest resolution for the map. The Danish Heat Atlas is using the bottom-up approach and has information on the single building level. Top-down models, on the other hand, use aggregated data on for example heat consumption and spatially disaggregate this using existing mapping information. An example of this approach is the Heat Roadmap Europe studies, which uses aggregated energy data on the NUTS0 to NUTS3 level, to be disaggregated spatially using more geographically detailed information on, e.g., population density and land use.

The data intensity of bottom-up mapping is often a hindrance, since it in many cases is impossible to acquire data in a high enough spatial resolution. Top-down models are therefore often the first step in establishing insight into the potentials of district heating and generating heat maps.

7.2.1. DATA ACCESS

Data access for heat mapping evolves around two separate issues. One is the existence and access to data, and the other is generalized versus local data.

The existence of data is always a prerequisite for any mapping. For heat mapping, especially bottom-up mapping is very depending on the existence of high-resolution spatial data. Secondly, this data has to be available for the developers of the heat maps. In the case of Denmark data is available on building level on some of the main parameters which determine heat demand through the BBR. Previously this was combined with indicator numbers on heat demand in Danish buildings depending on the type, age, and size. This has further been improved by data on the specific heat consumption in many Danish buildings, which was used to develop the latest version of the Danish Heat Atlas, as described in Chapter 6. In the Danish case, high-resolution data both exists and is available for heat mapping, although the availability comes with restrictions and does not exist for everyone.

In Paper 4, a heat map of Belgium is investigated for the Province of Limburg. This map is also developed using a bottom-up approach where energy consumption data from natural gas distribution companies was used to generate information on heat consumption. However, in this case, the data was kept confidential to all parties outside the distribution companies. This was done by obscuring the data in the heat map and to a large extent removing the possibility of identifying the exact location of the heat demands. The Belgium map based on local data is compared to the heat demand map produced in the Heat Roadmap Europe 3 STRATEGO study based on aggregated energy statistics.

In general, heat demand data rarely exists for all buildings in an area. In the Danish case, the data is collected from utility companies that provide energy products for heating. This means that secondary heating sources, biomass-based heating, and electric heating are not reported. The FIE database is therefore not expected to contain information on heat demand of all buildings. This can be handled by using the existing data to estimate heat demands in the remaining buildings. The approach in Belgium is very similar to the Danish but with one difference: in Belgium, the access to the data was restricted to people in the distribution companies. This means that the researcher working on the heat map are not allowed direct insight into the consumption data. It is instead handled by the distribution company, which then generates input data for the heat map, including buildings outside of their supply zones. As seen in Paper 4, this makes it difficult to check the quality of their assumptions and results. Furthermore, the approach means that the actual location of heat demands are obscured to a degree where it hinders the usability of the produced map by making it difficult to identify the actual location of the heat demand.

The comparison is made for each of the municipalities in the Province of Limburg since it is not possible to identify the specific location of the heat demands in the Belgium map. When comparing the heat demand found in the Belgian study to those found in the Heat Roadmap Europe study some differences appear. Figure 15 shows the heat demand for each of the municipalities sorted by the population number. Overall, there is a fair agreement in the tendencies for the increasing heat demand with an increasing population. However, the differences between the predictions are sometimes rather large, and three municipalities, in particular, turned out to have very different predictions in the two maps. The method used in the Heat Roadmap Europe study results in an almost linear correlation between the heat demand and the population. This is due to the method using a per capita heat demand value. The small differences occur due to differences in the prediction of the service sector and small differences climatically. The method is therefore not able to fully reflect the local differences and identify the local extremes. However, the method in many cases has a good agreement with the map produced using local data. Furthermore, the data can be used freely and is able to identify the location of the heat demands better. The method used in Heat Roadmap Europe is in the newest version being further improved using an Ordinary Least Square multilinear regression method described in [5].

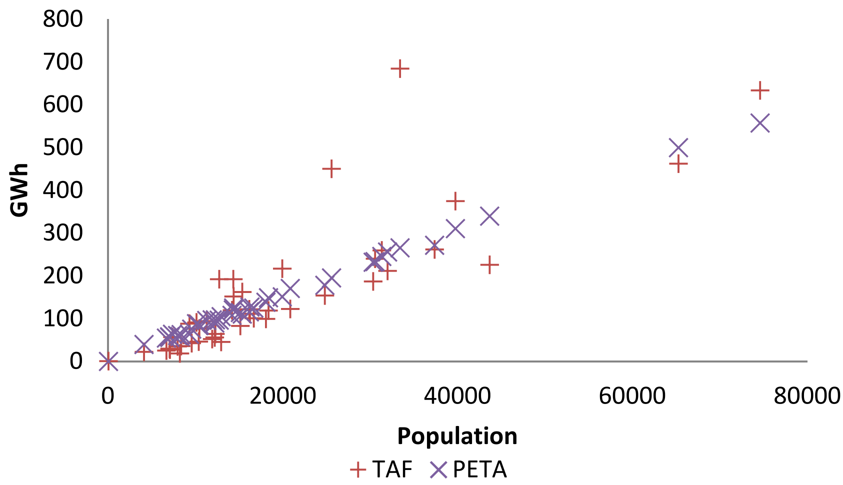

Figure 15: Heat demand in the municipalities sorted by the population. TAF = Thermal Atlas Flanders is the local Belgium map, PETA = Pan-European Thermal Atlas is the Heat Roadmap Europe map [4].

In many other countries, similar data on heat demand to the ones existing in Belgium, and Denmark exists. The coverage of the data is often defined by the coverage of communal heating services, which in some countries is relatively low. However, the access to the data is often restricted and spread out across several distribution companies without a single point of contact. This makes it difficult to produce heat maps using local data, and as a result, it often becomes very time consuming and therefore costly. As described in Chapter 2 and Chapter 4, the basis for much of the available data in Denmark was laid 30-40 years ago. A similar collection of data could be possible across Europe in all the countries without already existing data. However, it would prove very difficult in terms of legal challenges in the area of data protection and differences in the public data structures across the European countries, and the effort might not match the improvement in results in heat demand mapping.

The Heat Roadmap Europe project and other similar projects aimed at producing maps in a uniform way across the borders of the individual countries. This enables easy comparison between the results in the different countries. On the other hand, it means that the specific local variations are not always reflected in the maps. Nevertheless, as a screening tool used to identify the regions with the highest potentials for district heating they work very well. At the same time, they enable mapping of heat demands in regions without local data or where the authorities do otherwise not have a focus on the heating sector.

CHAPTER 8. DISCUSSION OF RESULTS

Heat demand mapping and heat atlases have for many years proven their ability to strengthen the knowledge base for heat planning. With a heat atlas, it is possible to calculate the specific potential for different heating solutions and combine it with for example heat savings. The combination of knowledge about specific heat demands and their location provides a quantitative foundation for energy system analysis for the heating sector. This allows for strategic decisions in the heating sector and further integration with the other energy sectors.

The situation across most countries in Europe and the world is very different from the Danish. In many countries, the mapping of heat demand is still in a developing stage and often lacking detailed data on the individual buildings. Instead, the models rely on other methods and more generic data. The models developed in Heat Roadmap Europe and similar projects are able to use aggregated European statistical data on heat demands and spatially disaggregate it using available data on, e.g., land usage and urbanization. A challenge is, however, that the urban planning and building density across Europe have very high variations. Similarly, the building characteristics and insulation levels are also very dependent on local traditions.

In Denmark, the mapping of building characteristics and energy use have been on the agenda since the 1970's. It has been an ongoing process to establish the data foundation needed for the planning of the Danish heating system. Today, data on the specific heat demand exists for more than one million Danish buildings and all Danish buildings are modeled in the Danish Heat Atlas with a heat demand corresponding to their characteristics. The benefits of the Danish Heat Atlas is the high spatial resolution and well-known characteristics of the individual buildings. However, the knowledge is far from perfect and lacks information on, e.g., the physical shape of the buildings and the size and location of windows.

It is seen that despite the comprehensive level of detail in the knowledge about the Danish building mass mapping cannot be completely accurate. There is still room for improvement with more advanced models for the heat demand based on the metered consumption data available. However, complete accuracy can never be expected and is perhaps not necessary since the Danish Heat Atlas is first and foremost intended as a screening tool for heat planning. It is not the intention to use the heat atlas as a direct planning tool for the location of for example the distribution grid for district heating since much better tools exist for that purpose.

8.1. THE DANISH HEAT ATLAS AS A SCREENING TOOL

The Danish Heat Atlas should be seen as a screening tool to be used in heat planning and to analyze the potential for district heating. The tool has been used in several studies highlighted throughout the thesis to analyze the potential for district heating in Denmark. The methods and scope of the different studies vary from analyzing the potential of replacing individual natural gas heating through analyzing the potential of expanding existing district heating grids and to comparing differences in the economic potentials depending on the economic approach.

As seen from Paper 3 the accuracy of the heat atlas varies largely between the different building types. The accuracy is only satisfying for the detached single-family houses, and even here, individual buildings can have very different consumptions from the estimates of the heat atlas. These inaccuracies underline that the heat atlas can only be used as a screening tool to identify areas of high potential for district heating, but with a need for more thorough analyses of the actual heat demand. It is, however, important to notice that the accuracy of the Danish Heat Atlas is performing well for the detached single-family houses, which is by far the largest category. In many cases, when looking at the expansion potential of district heating, most of the buildings belong to this category. The screening results, therefore, give good knowledge on the majority of buildings allowing for a more thorough investigation to focus on the few specific buildings with a higher inaccuracy. This can help to reduce the costs of investigating district heating potentials.

With the addition of a more detailed distribution grid model in Paper 2, the heat atlas estimates better the realistic cost for the investment in the grid. The model reflects the heat demand of the individual buildings in the costs and estimations of heat losses for the distribution grid and is, therefore, a clear upgrade from the simple distribution grid cost estimations made in Paper 1. The model, however, is not a general optimization model. Instead, it finds the shortest (least cost) route to connect each building with a central point within the potential district heating area. When routes overlap, they are summarized, and the pipe dimension is calculated based on the total need for the specific section. The model often finds several parallel routes, which in an optimization model would be merged into one route only. The model is therefore likely to overestimate the cost of the distribution grid. However, while GIS allows for a fast and consistent assessment of costs, it might not be the optimal tool for optimization of the layout of a distribution grid. Algorithms exist for network analysis with a focus on optimizing the distance of the grid; some might even consider optimizing the capacity as well. However, a district heating grid needs a detailed hydraulic calculation to ensure the optimal balance in pressure and temperature throughout the grid. Further, both pressure and temperature should be optimized to the seasonal changes in the heat demand. Other programs than GIS are likely to be better at this type of optimization. For the economic calculations, a good estimate of the cost of the distribution grid is enough for realistic district heating cost estimations.

Overall, the heat atlas allows for an easily accessible estimation of heat demands within any geographical entity. This allows for screenings of district heating potentials and costs based on a given set of assumptions to be performed within a relatively short timeframe. The heat atlas should, therefore, be used as a decision support tool analyzing different scenarios.

8.2. THE DANISH HEAT ATLAS AS A DECISION SUPPORT TOOL

It is possible to decide in which areas to investigate further the potential of district heating based on screenings done using the heat atlas. As seen in Paper 1 it is possible to initiate the screening based on different sets of assumptions for the economic approach. In Paper 2, different scenarios are analyzed for the district heating potential with changes both in the temperatures in the district heating pipes and in the end-user heat demands. This type of scenario analysis allows the heat atlas to be used as a decision support tool capable of analyzing the changes in the outcome of the model based on different assumptions.

The heat demand model in the heat atlas and the analysis of district heating costs can also be combined with mapping of potential renewable resources for heat production. Together with mapping of resources, it is possible also to investigate the different options for production of district heating.

The projects [6,47] were initiated by two Danish Regions enabling the policy makers to get an estimation of the district heating potential within the local municipalities. This enables the municipalities to identify local potentials for district heating and based on the screenings initiate further investigations and more detailed calculations of the potential of expanding the coverage of existing district heating networks. The results of the heat atlas analyses done in the reports thereby allow the policy makers to obtain an easily understandable knowledge and actively use it to initiate further investigations.

Knowledge of heat demands in Danish buildings is likely to further improve over the years. The FIE data used in the generation of the 5th version of the heat atlas is supposed to be directly integrated into the buildings and dwelling register allowing the owners of buildings to monitor the yearly heat consumption easily. This will also allow for even better predictions of heat demand across all Danish buildings since the data will already be linked correctly with the building data from the BBR register. As seen in Paper 3, the accuracy still needs improvements across most building types. Therefore, the work with the Danish Heat Atlas is far from finished. At the present point in time, however, yearly consumption data for Danish buildings are already well developed, and further improvements in accuracy are not likely to substantially change the heat demand estimations.

CHAPTER 9. CONCLUSION

This thesis has presented work on developing an updated edition of the Danish Heat Atlas based on consumer data. A better understanding of the differences in approaches of the economic assessment of district heating has been obtained by comparing consumer-economic and socio-economic expansion potentials: Furthermore, a new distribution grid model has been developed using the spatial location and estimated heat demands of the consumers as inputs. Finally the potential of using mapping of heat demands outside Denmark has been investigated by comparing two different heat maps for the Province of Limburg in Belgium.

Paper 1 and Paper 2 document the suitability of the heat atlas as a screening tool for district heating potentials with different scenarios. Paper 1 has a focus on the different economic approaches and investigates the expansion potential for both socio-economy and consumer-economy. The overall potential is found to be highest for the socio-economic approach. Furthermore, there is not always an overlap between socio-economic potentials and consumer-economic potentials, meaning that the consumers under the current economic conditions are not always inclined to invest in line with what is best for the society. Paper 2 focuses on the changes in expansion potential following the expected decrease in heat demand. A reference scenario under current conditions is compared to a future scenario with 50% lower heat demands for space heating. This results in a drastic reduction in the expansion potential. A third scenario investigates the potential for low-temperature district heating to mitigate the reduction in expansion potential. The study shows that converting to low-temperature district heating and the resulting reduction in heat losses by itself is not enough to fully mitigate the consequence of the reduced heat demand. The cost of heat production also has to become lower with the reduction of heat demand.

The study in Paper 2 further resulted in a better distribution grid model. The model is not an optimization model. Instead, it finds the shortest route from each building to a central point within the urban zone. The model is able to estimate the pipe dimension needed for the district heating grid together with the expected heat loss. The distribution grid costs and heat losses can, therefore, be calculated based on the heat demand of the individual buildings within the urban zone. This results in a better economic estimation of the cost of the distribution grid than in previous studies.

The work done in Paper 2 and Paper 3 builds upon the development of a new version of the Danish Heat Atlas. The heat demand in the buildings is estimated based on the type and age of the building using measured heat demands for approximately 1 million buildings per year for the years 2010-2014. In this way, the metered heat consumption data of Danish buildings are now the foundation of the heat demand estimation of the Danish Heat Atlas. This data further allows for an investigation of the accuracy of the heat atlas in Paper 3. The analysis is done by comparing the estimated heat demand with the measured heat demand for all buildings with a measured heat demand. The comparison is both done based on the geographical location of buildings within the urban zones and based on the building types and the selection of random samples within each building type. The analysis shows that the heat atlas only accomplished a satisfying accuracy for the detached single-family buildings. For the other categories, further work is needed to improve the accuracy of the estimation of heat demands. This, however, means that the heat demand estimation for the largest group of buildings is accurate already at a relatively low number of buildings. Because of that detailed investigations of heat demands is only needed for buildings outside of this category resulting in substantially less work in many cases.

Paper 4 compares two other heat atlases developed using different methodologies. The Flemish heat map is developed using data from the individual buildings similar to the method used in the Danish Heat Atlas, and the Pan-European Thermal Atlas is developed using aggregated statistical data on heat demands in Europe. Due to the way the heat demand has been spatially presented in the Flemish heat map the estimated heat demand of the two maps are compared for the municipalities in the Province of Limburg and not on a higher spatial resolution. The comparison shows that both methods in many cases predict similar heat demands, although with some quite big local variations. This is likely due to local variations in heat demand, which are difficult to predict for the European-scale heat mapping. As a solution, it is proposed to use heat maps based on measured heat demand values as a training tool for European-scale heat mapping. The Danish Heat Atlas is a good candidate for such tasks with the detailed knowledge of the individual buildings and their heat demand. The abilities of the Danish Heat Atlas is further improved with knowledge of the accuracy for the individual building types and further improvements to the accuracy in the future.

LITERATURE LIST

[1] Grundahl L, Nielsen S, Lund H, Möller B. Comparison of district heating expansion potential based on consumer-economy or socio-economy. Energy 2016. doi:10.1016/j.energy.2016.05.094.

[2] Nielsen S, Grundahl L. District Heating Expansion Potential with Low-temperature and End-Use Heat Savings, Final draft, submitted for publication n.d.

[3] Grundahl L, Nielsen S. Accuracy in numbers, heat atlas accuracy compared to real-world measurements, in preparation n.d.

[4] Grundahl L, Renders N, Möller B, Cornelis E. Comparing two heat maps developed using different methodologies and data types for the Province of Limburg in the Flemish region of Belgium, Submitted for Journal of Sustainable Energy Planning and Management (Status: under review) n.d.

[5] Möller B, Wiechers E, Persson U, Grundahl L, Connolly D. Heat Roadmap Europe - Identifying Local Heat Demand and Supply Areas with a European Thermal Atlas, Final draft, ready for submission n.d.

[6] Nielsen S, Grundahl L. Fjernvarmeanalyse i Region Nordjylland, contribution to report. 2015.

[7] Nielsen S, Grundahl L, Eriksen RB, Jessen K. F & U Energiforbrug i Bygninger. 2017.

[8] Grundahl L, Nielsen S. EnergyMaps 2016. www.energymaps.eu.

[9] Nielsen S, Grundahl L. The Danish Heat Atlas 2016 - Documentation, Draft version 2. 2016.

[10] Energistyrelsen. Dansk klimapolitik n.d. https://ens.dk/ansvarsomraader/energi-klimapolitik/fakta-om-dansk-energi-klimapolitik/dansk-klimapolitik (accessed September 27, 2017).

[11] Regeringen. For et friere, rigere og mere trygt Danmark - regeringsgrundlag. 2016.

[12] Ingeniørforeningen IDA. IDAs Klimaplan 2050. 2009.

[13] Mathiesen BV, Lund H, Hansen K, Ridjan I, Djørup S, Nielsen S, et al. IDA's Energy Vision 2050: A Smart Energy System strategy for 100% renewable

Denmark. Aalborg: 2015.

[14] Lund H, Mathiesen B V. Energy system analysis of 100% renewable energy systems-The case of Denmark in years 2030 and 2050. Energy 2009;34:524–31. doi:10.1016/j.energy.2008.04.003.

[15] Connolly D, Mathiesen BV. A technical and economic analysis of one potential pathway to a 100% renewable energy system. Int J Sustain Energy Plan Manag 2014;1:7–28. doi:10.5278/ijsepm.2014.1.2.

[16] Hong L, Lund H, Mathiesen BV, Möller B. 2050 pathway to an active renewable energy scenario for Jiangsu province. Energy Policy 2013;53. doi:10.1016/j.enpol.2012.10.055.

[17] Connolly D, Lund H, Mathiesen BV, Østergaard PA, Möller B, Nielsen S, et al. Smart Energy Systems: Holistic and Integrated Energy System for the era of 100% Renewable Energy. 2013.

[18] Hvelplund F, Østergaard P, Möller B, Mathiesen BV, Connolly D, Andersen AN. Analysis: Smart Energy Systems and Infrastructures. 2014. doi:10.1016/B978-0-12-410423-5.00006-7.

[19] Connolly D, Lund H, Mathiesen B V. Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renew Sustain Energy Rev 2016;60. doi:10.1016/j.rser.2016.02.025.

[20] Mathiesen BV, Lund H, Connolly D, Wenzel H, Østergaard PA, Möller B, et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54. doi:10.1016/j.apenergy.2015.01.075.

[21] Lund H, Andersen AN, Østergaard PA, Mathiesen BV, Connolly D. From electricity smart grids to smart energy systems – A market operation based approach and understanding. Energy 2012;42:96–102. doi:10.1016/j.energy.2012.04.003.

[22] Lund H, Thellufsen JZ, Aggerholm S, Wittchen KB, Nielsen S, Mathiesen BV, et al. Heat Saving Strategies in Sustainable Smart Energy Systems. Int J Sustain Energy Plan Manag 2014;4. doi:10.5278/ijsepm.2014.4.2.

[23] Lund H, Hvelplund F, Mathiesen BV, Østergaard P a., Christensen P, Connolly D, et al. Coherent Energy and Environmental System Analysis. 2011.

[24] Lund H, Hvelplund F, Østergaard P, Möller B, Mathiesen BV, Connolly D, et al. Renewable Energy Systems. Elsevier; 2014. doi:10.1016/B978-0-12-410423-5.00006-7.

[25] Nuytten T, Claessens B, Paredis K, Van Bael J, Six D. Flexibility of a combined heat and power system with thermal energy storage for district heating. Appl Energy 2013;104. doi:10.1016/j.apenergy.2012.11.029.

[26] Ommen T, Markussen WB, Elmegaard B. Heat pumps in combined heat and power systems. Energy 2014;76. doi:10.1016/j.energy.2014.09.016.

[27] Ridjan I, Mathiesen BV, Connolly D. Terminology used for renewable liquid and gaseous fuels based on the conversion of electricity: A review. J Clean Prod 2016;112:3709–20. doi:10.1016/j.jclepro.2015.05.117.

[28] Pensini A, Rasmussen CN, Kempton W. Economic analysis of using excess renewable electricity to displace heating fuels. Appl Energy 2014;131. doi:10.1016/j.apenergy.2014.04.111.

[29] Averfalk H, Ingvarsson P, Persson U, Gong M, Werner S. Large heat pumps in Swedish district heating systems. Renew Sustain Energy Rev 2017;79:1275–84. doi:10.1016/j.rser.2017.05.135.

[30] Lund R, Persson U. Mapping of potential heat sources for heat pumps for district heating in Denmark. Energy 2016. doi:http://dx.doi.org/10.1016/j.energy.2015.12.127.

[31] Meyabadi AF, Deihimi MH. A review of demand-side management: Reconsidering theoretical framework. Renew Sustain Energy Rev 2017;80:367–79. doi:10.1016/j.rser.2017.05.207.

[32] Lund H, Østergaard PA, Connolly D, Ridjan I, Mathiesen BV, Hvelplund F, et al. Energy Storage and Smart Energy Systems. Int J Sustain Energy Plan Manag 2016;11:3–14. doi:10.5278/ijsepm.2016.11.2.

[33] Lazkano I, Nøstbakken L, Pelli M. From fossil fuels to renewables: The role of electricity storage. Eur Econ Rev 2016;99:113–29. doi:10.1016/j.euroecorev.2017.03.013.

[34] Olsthoorn D, Haghighat F, Mirzaei PA. Integration of storage and renewable energy into district heating systems: A review of modelling and optimization. Sol Energy 2016;136. doi:10.1016/j.solener.2016.06.054.

[35] Gas Storage Denmark. About Gas Storage Denmark n.d.

http://gaslager.energinet.dk/EN/about/Pages/default.aspx (accessed September 28, 2017).

[36] International Energy Agency. Natural gas market review 2007 - Security in a globalising market to 2015. 2007.

[37] Ridjan I, Mathiesen BV, Connolly D, Duić N. The feasibility of synthetic fuels in renewable energy systems. Energy 2013;57. doi:10.1016/j.energy.2013.01.046.

[38] Association of the European Heating Industry. European Heating and Cooling Strategy n.d. http://www.ehi.eu/article/european-heating-and-cooling-strategy (accessed September 28, 2017).

[39] European Commission. An EU Strategy on Heating and Cooling. 2016.

[40] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. Energy 2014;68:1–11. doi:10.1016/j.energy.2014.02.089.

[41] Trier D. Towards Solar District Heating with More than 70% Solar Fraction. Energy Procedia, vol. 70, Elsevier; 2015, p. 580–6. doi:10.1016/j.egypro.2015.02.163.

[42] Hansen L. Har vi den rigtige model for varmeplanlægning? n.d. http://www.danskfjernvarme.dk/vi-mener/debatindlaeg/arkiv/2010/har-vi-den-rigtige-model-for-varmeplanlægning,-q-, (accessed September 23, 2017).

[43] Erhvervsstyrelsen. Bekendtgørelse af lov om planlægning 2015.

[44] Ministry of the Environment. Spatial planning in Denmark. 2012.

[45] Energistyrelsen. Bekendtgørelse af lov om varmeforsyning 2017.

[46] Energi- Forsynings- og Klimaministeriet. Aftaler og politiske udspil n.d. http://efkm.dk/ministeriet/aftaler-og-politiske-udspil/ (accessed September 23, 2017).

[47] Nielsen S, Lykkemark B. Fjernvarmeanalyse i Region Midtjylland - afgrænsning. 2014.

[48] Energi- Forsynings- og Klimaministeriet. Bekendtgørelse om tilslutning m.v.

til kollektive varmeforsyningsanlæg 2016.

[49] Energistyrelsen. Our Responsibilities n.d. https://ens.dk/en/our-responsibilities (accessed September 23, 2017).

[50] Energitilsynet. Profile n.d. http://energitilsynet.dk/tool-menu/english/ (accessed September 23, 2017).

[51] Meyer NI. Første officielle energiplan 1976 2000. http://www.klimadebat.dk/foerste-officielle-energiplan-1976-r316.php (accessed September 21, 2017).

[52] Meyer NI. Første alternative energyplan 1976 2000. http://www.klimadebat.dk/foerste-alternative-energiplan-1976-r317.php (accessed September 21, 2017).

[53] Energiministeriet. Bekendtgørelse af Lov om varmeforsyning 1983.

[54] Danish Energy Agency. Regulation and planning of district heating in Denmark. 2017.

[55] Energiministeriet. Aftale mellem regeringen og socialdemokratiet om den fremtidige eludbygning og om en forstærket indsats på energibesparelsesområdet 1986.

[56] Aftale mellem regeringen og Socialdemokratiet om øget anvendelse af kraftvarme, naturgas og andre miljøvenlige brændsler samt om eludbygningen i 90'erne 1990.

[57] Energistyrelsen. Fjernvarmens rolle i den fremtidge energiforsyning. 2014.

[58] Danmarks Statistik. Danmarks statistik - ENE1HO: ENERGIREGNSKAB I SPECIFIKKE ENHEDER (OVERSIGT) EFTER TILGANG OG ANVENDELSE OG ENERGITYPE 2016. http://www.statistikbanken.dk/statbank5a/Selectout/pivot.asp (accessed September 28, 2017).

[59] Stein O. Energiindhold i brændsler n.d. http://www.folkecenter.dk/mediafiles/folkecenter/energibesparelse/energiindhold-i-braendsler.pdf (accessed September 23, 2017).

[60] Nielsen S. Spatial Heat Planning and Heat Demand Reductions in Buildings. Aalborg University, 2013.

[61] Kristensen PR, Sletbjerg MR. Energydata - Planning and analysis in a GIS 1998.

[62] Erhvervsstyrelsen. PlansystemDK n.d. https://erhvervsstyrelsen.dk/plansystemdk.

[63] Petrovic SN, Karlsson KB. Danish heat atlas as a support tool for energy system models. Energy Convers Manag 2014;87:1–14. doi:10.1016/j.enconman.2014.04.084.

[64] Möller B, Nielsen S. High resolution heat atlases for demand and supply mapping. Int J Sustain Energy Plan Manag 2014;1:41–58. doi:http://dx.doi.org/10.5278/ijsepm.2014.1.4.

[65] Nielsen S. A geographic method for high resolution spatial heat planning. Energy 2014;67:351–62. doi:10.1016/j.energy.2013.12.011.

[66] Nielsen S, Möller B. GIS based analysis of future district heating potential in Denmark. Energy 2013;57:458–68. doi:10.1016/j.energy.2013.05.041.

[67] Möller B, Lund H. Conversion of individual natural gas to district heating: Geographical studies of supply costs and consequences for the Danish energy system. Appl Energy 2010;87:1846–57. doi:10.1016/j.apenergy.2009.12.001.

[68] State of Green. New white paper on district energy n.d. https://stateofgreen.com/en/profiles/state-of-green/news/new-white-paper-on-district-energy (accessed September 28, 2017).

[69] Folketinget. Lov om bygnings- og boligregistrering 1976.

[70] Ministeriet for By B og L. Bekendtgørelse af lov om bygnings- og boligregistrering 2013.

[71] Boligministeriet. Cirkulære om etablering af bygnings- og boligregistrering 1977.

[72] Boligministeriet. BBR-MEDDELELSE 1977 NO. 1 Retningslinier for brugen af bygnings- og enhedsanvendelseskoder i bygnings- og boligregistret 1977.

[73] Bygnings og Boligregistret. BBR-instruks 2015. http://bbr.dk/instruks/0/31 (accessed October 18, 2017).

[74] Erhvervs og Byggestyrelsen. Bekendtgørelse om energiforsyningsselskabernes indberetningspligt til Bygnings- og

Boligregistret (BBR) 2010.

[75] Ministeriet for By B og L. Bekendtgørelse om energiforsyningsvirksomhedernes indberetningspligt til Bygnings- og Boligregistret (BBR) 2013.

[76] Erhvervs- og Byggestyrelsen. FIE brugervejledning. n.d.

[77] Styrelsen for Dataforsyning og Effektivisering. Kortforsyningen n.d. https://www.kortforsyningen.dk/.

[78] Kragh J, Wittchen KB. Danske bygningers energiforbrug i 2050. 2010.

[79] Danmarks Statistik. Statistikbanken BOL105 2017. http://www.statistikbanken.dk/bol105 (accessed September 28, 2017).

[80] Almeida M, Ferreira M. Cost effective energy and carbon emissions optimization in building renovation (Annex 56). Energy Build 2017;152:718–38. doi:10.1016/j.enbuild.2017.07.050.

[81] Danish Energy Agency. Forudsætninger for samfundsøkonomiske analyser på energiområdet. 2014.

[82] Danish Energy Agency. Technology Data for Energy Plants Generation of Electricity and District Heating , Energy Storage and Energy Carrier Genaration and Conversion 2015:1–229.

[83] Danish Energy Agency. Technology Data for Energy Plants Individual Heating Plants and Energy Transport. 2013.

[84] Energitilsynet. Energitilsynets prisstatistik for fjernvarmeområdet. 2014.

[85] Dansk Fjernvarme. Fjernvarmeprisen 2014. 2014.

[86] Bygnings og Boligregistret. Energiforbrugsdata n.d. http://bbr.dk/energiforbrugsdata (accessed September 30, 2017).

[87] Openlayers. Openlayers.org n.d. https://openlayers.org/ (accessed September 30, 2017).

[88] Persson U, Werner S. Heat distribution and the future competitiveness of district heating. Appl Energy 2011;88:568–76. doi:10.1016/j.apenergy.2010.09.020.

[89] Dansk Fjernvarme. Fakta om fjernvarme n.d. http://www.danskfjernvarme.dk/presse/fakta-om-fjernvarme (accessed October 1, 2017).

[90] Eurostat. Eurostat - Your key to European statistics n.d. http://ec.europa.eu/eurostat (accessed September 22, 2017).

[91] Hoos E. Keynote speak by Eva Hoos, Policy Officer in DG Energy, 4DH conference 2015 2015.

[92] Connolly D, Mathiesen BV, Østergaard PA, Möller B, Nielsen S, Lund H, et al. Heat Roadmap Europe 1: First Pre-Study for the EU27. Aalborg: 2012.

[93] European Commission. Heating and cooling - European Commission n.d. https://ec.europa.eu/energy/en/topics/energy-efficiency/heating-and-cooling (accessed October 20, 2017).

[94] The Guardian. Wind from Britain, solar from the Sahara, geothermal from Iceland 2015. https://www.theguardian.com/news/2015/nov/22/european-supergrid-renewable-energy (accessed October 1, 2017).

[95] Connolly D, Mathiesen BV, Østergaard PA, Möller B, Nielsen S, Lund H, et al. Heat Roadmap Europe 2: Second Pre-Study for the EU27. Aalborg: 2013.

[96] Connolly D, Hansen K, Drysdale D, Lund H, Mathiesen BV, Werner S, et al. Heat Roadmap Europe 3 (STRATEGO): Translating the Heat Roadmap Europe Methodology to Member State Level. Aalborg: 2015.

[97] Heat Roadmap Europe. Heat Roadmap Europe n.d. http://heatroadmap.eu/ (accessed October 1, 2017).

[98] Thermos. Thermos: Home n.d. https://www.thermos-project.eu/home/ (accessed October 1, 2017).

[99] Hotmaps. Hotmaps - The open source mapping and planning tool for heating and cooling n.d. http://www.hotmaps-project.eu/ (accessed October 1, 2017).

[100] PLANHEAT. PLANHEAT - Home n.d. http://planheat.eu/ (accessed October 1, 2017).

[101] European Parliament. Directive 2012/27/EU. Off J Eur Union 2012;L315/1:1–56.

[102] European Commission. Communication from the commission to the european

parliament, the council, the european economic and social committee and the committee of the regions - An EU Strategy on Heating and Cooling. Brussels: 2016.

Appendix A. Paper 1

Comparison of district heating expansion potential based on consumer-economy or socio-economy

Lars Grundahl[a], Steffen Nielsen[a], Henrik Lund[a], Bernd Möller[a,b]

[a] Department of Development and Planning, Aalborg University, Skibbrogade 5, DK-9000 Aalborg, Denmark

[b] Department of Energy and Environmental Management, Europa-Universität Flensburg, Munketoft 3b, DE-24937 Flensburg, Germany

Published in Energy

https://doi.org/10.1016/j.energy.2016.05.094

Appendix B. Paper 2

District Heating Expansion Potential with Low-temperature and End-Use Heat Savings

Steffen Nielsen[a], Lars Grundahl[b]

[a] Aalborg University, Rendsburggade 14, Aalborg, Denmark

[b] Aalborg University, A. C. Meyers Vænge 15, Copenhagen, Denmark

Submitted for publication

Appendix C. Paper 3

Accuracy in numbers, heat atlas accuracy compared to real-world measurements

Lars Grundahl[a], Steffen Nielsen[b]

[a] Department of Development and Planning, Aalborg University, A. C. Meyers Vænge 15, DK-2450 København SV, Denmark

[b] Department of Development and Planning, Aalborg University, Rendsburggade 14, DK-9000 Aalborg, Denmark

In preparation

Appendix D. Paper 4

Comparing two heat maps developed using different methodologies and data types for the Province of Limburg in the Flemish Region of Belgium

Lars Grundahl[a], Nele Renders[b], Bernd Möller[a,c], Erwin Cornelis[b]

[a] Department of Development and Planning, Aalborg University, A. C. Meyers Vænge 15, DK-2450 Copenhagen, Denmark

[b] VITO NV, Boeretang 200, 2400, Mol, Belgium

[c] Department of Energy and Environmental Management, Europa-Universität Flensburg, Munketoft 3b, DE-24937 Flensburg, Germany

Submitted for publication

ISSN (online): 2446-1628
ISBN (online): 978-87-7210-097-5

AALBORG **UNIVERSITY PRESS**